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Technology Plan for the Terrestrial Planet Finder

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Abstract

This document presents an overview of planned pre-phase A technology development activities for the period FY2003-FY2006 aimed at enabling the Terrestrial Planet Finder (TPF) mission and selecting the most viable mission architecture from among several candidates. TPF's science objective is to search for and characterize Earth-like planets around a statistically significant sample of nearby stars. The technologies needed for a TPF mission have been identified over the past few years through architecture studies performed by JPL and several industrial/academic teams. These studies identified two viable TPF mission architectures classes: (1) mid-infrared nulling interferometers (either on a large deployed structure or utilizing an array of spacecraft flying in precision formation), and (2) visible/near-infrared coronagraphs. The primary objective of TPF pre-phase A activities through 2006 will be to demonstrate the technological feasibility of the candidate architectures and reach a decision on which one(s) can enable implementation and operation of the TPF mission in the 2010-2020 timeframe consistent with technical, scientific and programmatic goals, objectives and constraints.

The most recent edition of this plan is available online at http://tpf.jpl.nasa.gov/.

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Introduction

The Terrestrial Planet Finder (TPF) mission is a key element of NASA's Office of Space Science (OSS) Navigator Program and is part of the roadmap for the OSS Astronomical Search for Origins (ASO) science theme. TPF is managed by the OSS Astronomy and Physics Division at NASA Headquarters.

NASA has delegated the responsibility for pre-formulation study activities, technology development, formulation, and implementation of the TPF mission to the Jet Propulsion Laboratory (JPL). TPF is managed as a Pre-Project Study in the Origins and Fundamental Physics Program Office at JPL, which is part of the Astronomy and Physics Directorate at the Laboratory.

This document presents an overview of planned pre-phase A technology development activities for the period FY2003-FY2006 aimed at enabling the Terrestrial Planet Finder (TPF) mission and selecting a viable mission architecture from among several candidate concepts. The defining science goal for TPF is to understand the formation and evolution of planets and, ultimately, of life beyond our Solar System. This goal requires a statistically significant census of planets of Earth-like mass, an understanding of the physical and biological processes that make a planet habitable and that might lead to the evolution of a "living" planet, and the direct examination of nearby planets for signs of life. Within this context, the science objective of TPF is to detect radiation from Earth-like planets located in the habitable zones of solar-type stars in order to (1) characterize the orbital and physical properties of detected planets to assess their habitability, and (2) characterize the atmospheres and search for potential biomarkers among the brightest Earth-like candidates. Current ground and space observatories cannot make these observations, nor is current technology adequate to implement such an observatory. Advances in a number of technologies are needed to confidently build a system that can satisfy the scientific objectives.

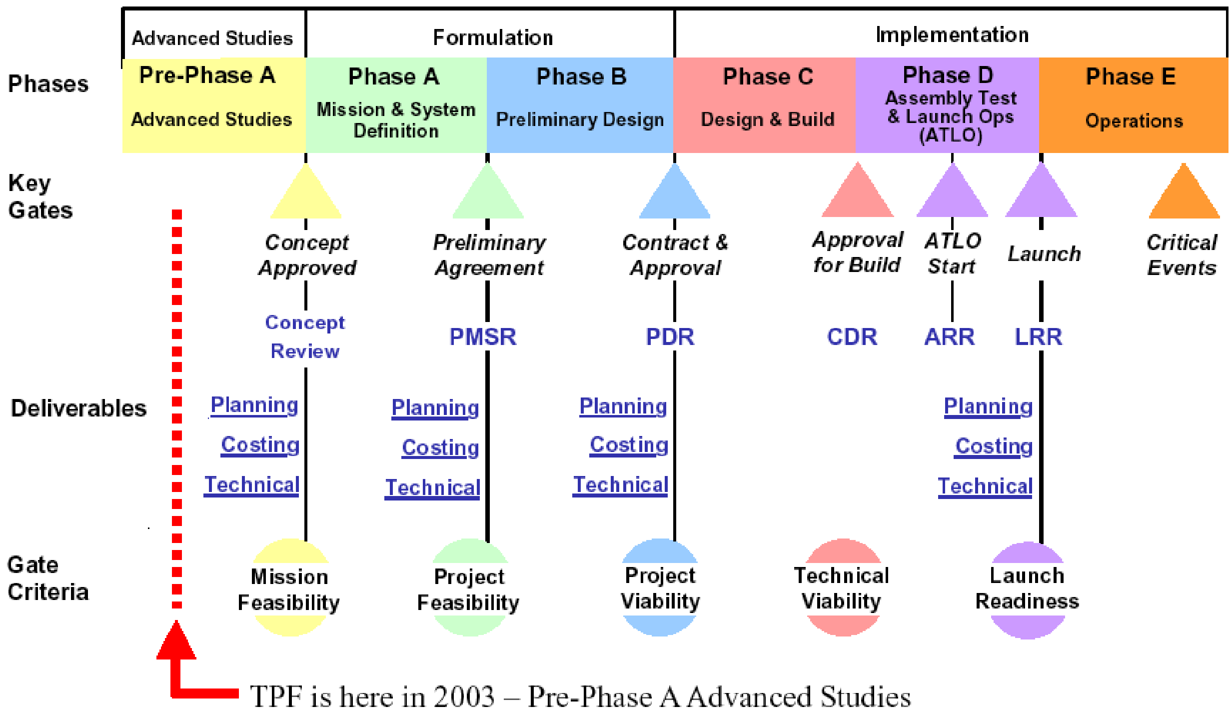
The technologies needed for a TPF mission have been identified over the past few years in architecture studies performed by JPL and several industry/academic teams. These studies identified two viable TPF mission architecture classes: (1) mid-infrared nulling interferometers (either on a large deployed structure or utilizing an array of spacecraft flying in precision formation), and (2) visible/near-infrared coronagraphs. The primary objective of TPF pre-phase A activities through 2006 will be to demonstrate the technological feasibility of the candidate architectures and reach a decision on which one(s) can enable implementation and operation of the TPF mission in the 2010-2020 timeframe consistent with technical, scientific and programmatic goals, objectives and constraints.

This document is divided into three main sections: (1) Introduction, (2) Technology Plan, and (3) Appendices. The Introduction section provides an overview of the project-level pre-phase A plans and sets the context for the planned technology development. The Technology Plan section describes the high level scope of work and associated performance metrics that will provide guidance for the project's efforts and enable assessment of progress over the period FY2003-FY2006. Significant changes affecting this section will require review and approval/concurrence by the signatories of this document. The

Appendices provide additional supporting detail that is focused on implementation of the Technology Plan. Routine changes in the implementation strategy such as budget adjustments, schedule changes, organizational changes, personnel changes, etc. will be reported through the standard project reporting process and will be reflected in the annual Program Operating Plan (POP) process.

Pre-Phase A Plan Overview

The Terrestrial Planet Finder (TPF) Project is in the first (or "pre-phase A" stage) of the NASA Project Life Cycle, shown below. In pre-phase A, a wide range of missions and technology concepts are explored, and the emphasis is on establishing top-level goals, science requirements, and the technological feasibility of the mission.



TPF is here in 2003 – Pre-Phase A Advanced Studies

In support of this pre-phase A effort, JPL led a team of scientists and engineers representing universities, industry, other NASA centers, and the European Space Agency during 1998 in a study of mission concepts capable of achieving TPF's science goals of finding and characterizing Earth-like planets around nearby stars. The results of this team's efforts were published (*TPF- A NASA Origins Program to Search for Habitable Planets*, May 1999) and reaffirmed the results of earlier studies (*Exploration of Neighboring Planetary Systems* (ExNPS) Report, August 1996), which concluded that an infrared interferometer represented the best approach to the challenge of detection and spectroscopic characterization of planets as small as the Earth around nearby stars. The team further concluded that an array of telescopes (each on its own spacecraft and with a central spacecraft housing the beam combining and astronomical instrumentation flying in precision formation) was the optimum mission architecture and would be feasible with realizable technological advances in several key areas.

In order to evaluate a wider range of concepts and consider the impact of technological advances in a number of areas, the TPF Project selected four industry-university teams in March 2000 to examine a broad range of mission architectures capable of achieving the TPF science goals. More than 60 mission concepts were initially explored. In January 2001, four architectural concepts were selected for further detailed study. At the completion of these studies in December 2001, the architectures that appeared most promising were visible-near infrared coronagraphs based on large single telescopes and mid-infrared interferometers (with multiple telescopes separated by 25–40 meters or more). In the case of the interferometers, both formation-flying and structurally-connected interferometers were considered promising.

The major goal of the TPF pre-phase A activity is to identify and select an architecture for the TPF mission. The architecture selection will be based heavily on the technological feasibility demonstrated for candidate architectures. Over the period FY2003 to FY2006, the TPF project will perform activities focused on achieving this goal no later than FY2006 to support a Phase A start in FY2007 and a launch by ~2015. The TPF Project has planned periodic opportunities to narrow the scope of the investigations or make an early downselect, based on results from the technology development and design teams or on programmatic factors.

This technology plan summarizes the top-level scope, approach, and metrics for development and acquisition of technology during the Advanced Study Phase (pre-phase A) to establish feasibility of a candidate TPF architecture(s) and support entry into Phase A. During this period, the project will focus on science, technology, and system design studies associated with the interferometer and coronagraph architectures. TPF will be a technologically rich mission requiring demonstration or inheritance of numerous technologies. NASA is committed to a well-funded technology development program, which will be carried out in the following context:

- The bulk of TPF funding will be targeted to demonstrate the key technologies needed for both architecture classes. The goal will be to develop the critical technologies necessary for discriminating between architectures to a NASA Technology Readiness Level (TRL) of ~5 by mid FY2006 (see page 91 for TRL definitions). Technology demonstration will be performed through a combination of efforts at JPL and significant competed/directed efforts in industry and at universities. Several major technology solicitations have already been executed or are in preparation.

- JPL, with support from industry and university experts and the TPF Science Working Group, will perform detailed mission studies of point designs for the coronagraphic and interferometric versions of TPF. The products of these studies will be concepts similar in nature and utility to the NGST "Yardstick" design developed by the Goddard Space Flight Center in the early stages of the James Webb Space Telescope (JWST) development.

- Approximately 10% of the total TPF budget will be allocated on an annual basis to support TPF preparatory science investigations and fellowships with the goal of better understanding the nature and, if possible, the frequency of occurrence of Earth-like planets around other stars. The highest priority science questions to which these investigations should respond will be determined by the TPF Science Working Group and described in a TPF Science Roadmap. These funds will be awarded through a combination of directed studies and competitive processes such as NASA Research Announcements (NRAs).

- Through a Letter of Agreement, now signed, TPF will coordinate with the European Space Agency's Darwin Project with the goal of achieving consensus on a common architecture for a potential joint planet-finding mission.

- Annual reviews will be held to assess the state of knowledge and development and assist in determining if termination, acceleration, or reduction of any technology efforts is warranted, or if an architecture selection is possible prior to 2006.

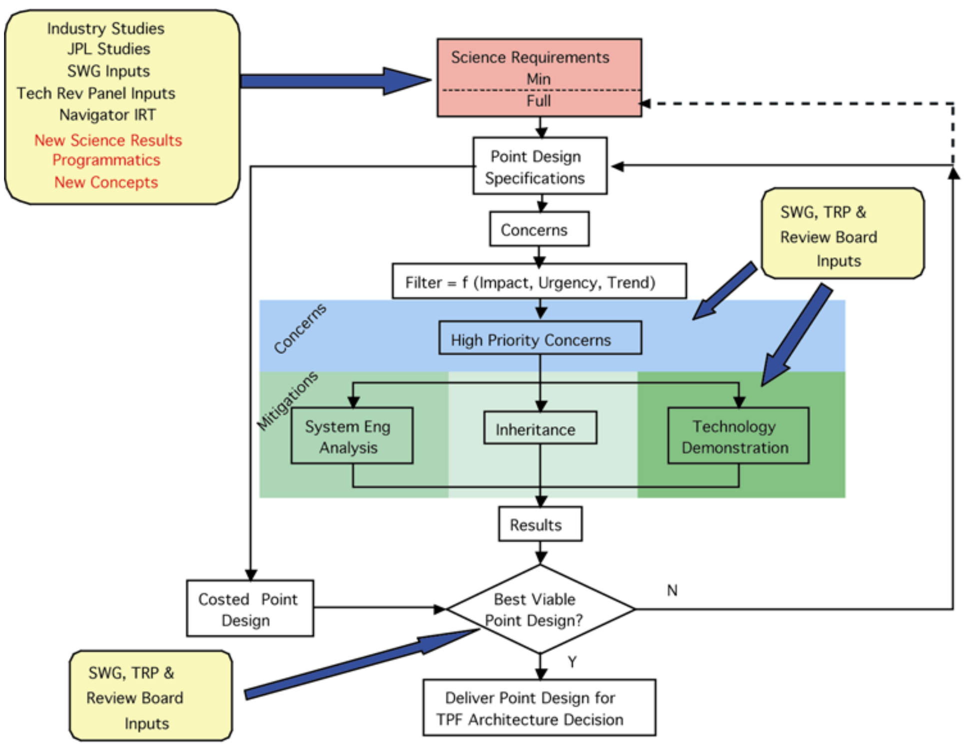
Contained in this document are the programmatic approaches, plans, and guidelines that are consistent with the current phase of TPF. Following the selection of a mission architecture, and confirmation at the Mission Concept review, TPF will proceed to the formulation phase (Phase A/B). The TPF design will be refined and key technologies developed to TRL 6 during the formulation phase. This document does not address technology demonstration plans for the Formulation Phase, nor does it address any potential precursor flight missions by NASA or in collaboration with ESA.

Technology Requirements

Previous architecture studies have provided a set of baseline technology needs and requirements that have been utilized to plan and initiate the technology development process for TPF. During pre-phase A, the TPF Science Working Group (SWG) will continue to define and refine the mission science requirements including both the science floor and the goals. These in turn will be passed on to the Design Teams, which will generate point designs and associated error budgets/specifications and identify technology needs and concerns, including performance requirements and priority.

The technology needs will then be assessed, and approaches to meet them will be identified. Mitigation approaches will include system engineering analysis, inheritance, and technology demonstration/development. Where technology development is required, the technology teams will be advised, and they will work to address the need. As the technology development proceeds and matures, results, including quantitative performance data will be passed back to the Design Teams. Thus, in an iterative process, the feasibility of the point designs will be determined, and the technology performance requirements will be updated.

Ultimately, the estimated cost of the candidate point designs will be determined by the engineering and design teams working with experienced cost analysts. Annual reviews will be held to evaluate progress in science, technology, and system design. This information and these results will be used in the architecture selection process. This process for establishing and refining technology requirements is shown schematically in the figure below.



Further Reading

Origins of Solar Systems Addendum to ROSS NRA
http://research.hq.nasa.gov/code_s/nra/current/NRA-02-OSS-01/appendA2.html - A.2.4

TPF Mission Architecture Study Reports (JPL Pub 02-017 8/02)
http://planetquest.jpl.nasa.gov/TPF/index.htm

Biomarkers Study (JPL Pub 01-008 6/02)
http://planetquest.jpl.nasa.gov/TPF/TPFrevue/BioJun02.pdf

JPL Architecture Study Summary Report (JPL Pub 02-011 6/02)
http://planetquest.jpl.nasa.gov/TPF/TPFrevue/FinlReps/JPL/tpfrpt1a.pdf

Exoplanet NRA Awards (2001)
http://research.hq.nasa.gov/code_s/nra/current/NRA-01-OSS-04/winners.html

TPF- A NASA Origins Program to Search for Habitable Planets (JPL Pub 99-3 5/99)
http://planetquest.jpl.nasa.gov/TPF/tpfBook/index.htm

A Road Map for the Exploration of Neighboring Planetary Systems (JPL Pub 96-22 8/96)
http://origins.jpl.nasa.gov/library/exnps/ExNPS.html

(All URLs above were valid as of the release date of this document)

Technology Plan

Overview

TPF will be a technologically challenging mission regardless of the architecture that is ultimately chosen. The recent studies have shown clearly that there are TPF architectures feasible for development and launch by the middle of the next decade. However, significant technical challenges exist for all of the candidate architectures studied. These must be overcome for at least one architecture before the mission can be realized. There must be adequate technology demonstration over the next few years, building on a technical base of earlier missions and ground-based activities.

Previous studies have concluded that most promising TPF architectures are visible/near-infrared coronagraphs based on large single telescopes and mid-infrared interferometers (with multiple telescopes separated by 25–40 meters or more). In the case of the interferometers, both formation-flying and structurally-connected interferometers were considered promising. The TPF Project, the TPF SWG, and the TPF Technology Review Panel performed comprehensive technical assessments of the various concept studies, and they all concurred. The TPF Science Working Group (SWG) noted that observations in either visible/near-infrared or mid-infrared wavelengths bands would provide adequate information for the detection and characterization of Earth-like planets because important signposts of habitability and even of primitive life itself exist in both bands. Thus, the TPF SWG suggested technology readiness, rather than a scientific preference for any particular wavelength region, will probably be the determining factor in the selection of the final mission architecture. In April 2002, the TPF Project recommended to NASA Headquarters that visible/near-infrared coronagraphs and mid-infrared interferometers (both formation flying and structurally connected types) be carried forward for detailed design studies and for the technology development activities described in this plan. NASA OSS concurred with this recommendation and directed JPL to proceed.

Approach

The TPF Technology Review Panel recommended that NASA pursue a sustained and well-funded technology demonstration program for both visible/near-infrared coronagraphs and mid-infrared nulling interferometers until one architecture clearly emerges as the leading concept. The TPF technology plan is premised on the parallel development of these competing mission architectures focusing on the technologies necessary to discriminate between architecture choices. The overall approach that was recommended, and is implemented in the technology plan, includes a combination of component-level demonstrations, subsystem and comprehensive laboratory testbeds, and integrated software models/simulators.

The project is organized into competing teams that will refine the mission architectures so that the performance requirements of the various technologies may be defined. The architecture-development teams are each composed of mission-design and technology-development teams. The mission-design teams develop and improve the mission designs to determine performance requirements and technology needs, and also perform trades and design changes based on inputs from the technology development teams. The technology development teams work to reduce mission risk by identifying candidate technologies for further development to meet mission needs, and then arrange to develop those technologies through a combination of JPL, NASA, and subcontracted industry and university efforts.

The TPF Project is committed to maintaining strong industry and university involvement. The Project will identify selected activities best suited for implementation in industry and academia. JPL will solicit, award, and manage a set of industry and university contracts to develop and demonstrate technologies for the candidate mission architectures.

In addition to the technology development efforts described here, the TPF Project also plans to take advantage of a rich technology inheritance from many outside sources for key technologies. Among these sources are NASA space missions presently in operation or development, such as the Hubble Space Telescope (HST), the Space InfraRed Space Telescope Facility (SIRTF), the Space Interferometry Mission (SIM), and the James Webb Space Telescope (JWST), as well as ground based observatories such as the Keck Interferometer and the Large Binocular Telescope Interferometer. A significant inheritance in support of the mid infrared interferometer architecture, and in particular the formation flying version, has been received from NASA's StarLight mission, the flight portion of which was recently cancelled. Much of the StarLight technical team and all of the project facilities have been incorporated into the TPF Project as of October 2002. Additional inheritance can be anticipated form various DOD (e.g. Air Force, DARPA) development activities and flight missions. A more complete listing of sources, including identification of technologies inherited and the degree of inheritance is given on page 68. The development of these technologies that the TPF Project expects to inherit will be tracked to ensure that the technologies will meet TPF needs, and the TPF technology development plans will be revised as necessary to adjust for any changes in the availability of inherited technologies.

The Architecture Concepts

The detection of Earth-like planets will not be easy. The targets are faint and located close to parent stars that are more than a million times (in the infrared) to more than a billion times (in the visible/near-infrared) brighter than the planets. However, the detection problem is well defined and can be solved using technologies that can be developed within the next decade.

Interferometers

At mid-infrared wavelengths, nulling interferometer designs using three or more 3 to 4 m telescopes—located on either an array of formation-flying spacecraft or on a large structure—would be capable of detecting the thermal radiation emitted by Earth-like planets around nearby stars. The largest area of technical risk for the infrared interferometers is not believed to be in the performance of the individual components, but in the operation of the various elements as a complete instrument. No insurmountable problems have been identified at the component or assembly level. Most of the required elements are either under development and making good progress or are reasonable extensions of technology being developed for other missions (SIRTF, JWST, SIM) and ground observatories (Keck and LBT Interferometers) that will be in place before TPF needs them. While considerable resources must be expended to bring the relevant component technologies to an appropriate level of readiness, a major focus of TPF technology development must be the demonstration of sub-system and system-level testbeds, simulators, and integrated models that will provide the necessary insight into the problems associated with TPF performance at the system level.

Visible/Near Infrared Coronagraphs

At visible/near infrared wavelengths, a large telescope equipped with a selection of advanced optics to reject scattered and diffracted starlight (apodizing pupil masks, coronagraphic stops, and deformable mirrors) would be capable of making direct images of extrasolar Earth-like planets. The principal conclusion with regard to the state of technology for the visible coronagraph is that the greatest technical risk for this architecture is in the demonstration, manufacturing, and implementation of the large ultra-low-wavefront-error (WFE) primary mirror and components associated with the challenging requirements for starlight suppression necessary to achieve the required very high contrast imaging capability. The coronagraphs themselves are functionally simple, and although the demands for system performance are challenging, none are thought to be insurmountable. Work is in progress on many of the required elements, and studies are underway with regard to possible approaches for mirror fabrication. A major focus of TPF technology development in support of this architecture is, and will continue to be, the demonstration of components, subsystem and system-level testbeds, simulators, and integrated models that will provide the necessary insight into the achievable levels of performance in the laboratory and problems associated with implementing this architecture in space for TPF.

Preliminary TPF Requirements, Key Technologies, and Performance Goals

Based on the architecture studies by the industry/academia teams (TPF Mission Architecture Study Reports, JPL Pub 02-017), the TPF Project has identified preliminary TPF requirements, key technologies to be developed, and associated performance goals to demonstrate feasibility of the various architectures. The identified key technologies and performance goals are consistent with current understanding of the TPF technology and mission needs, as identified through several years of study of candidate architectures (mid-infrared interferometers and visible/near infrared coronagraphs). Development tasks have also been identified to address the key technologies within the TPF Project Work Breakdown Structure (WBS). The preliminary requirements, key technologies, performance goals and their associated development tasks are identified in the tables on the next two pages.

Preliminary TPF Requirements, Key Technologies, and Performance Goals

Coronagraph Technologies	Preliminary TPF Requirement	Technology Demonstration Goal
Large high-precision optics	<25 kg/m^2; <7 nm rms surface error at 4–100 cycles/aperture; 4 to 10 m class	<60 kg//m^2 <7 nm rms surface error at 4–100 cycles/aperture 2 m class
Image and pupil-plane masks and stops	Masks consistent with 10^{-9} contrast requirement	Masks consistent with 10^{-9} contrast requirement
Wavefront sensing and control	Demonstrate sensing and control to $\lambda/10^4$ in mid-spatial frequencies in a flight-like system.	Demonstrate sensing and control to $\lambda/10^4$ in mid-spatial frequencies in a flight-like system.
High actuator-density deformable mirror	Deformable mirror with accuracy and control consistent with 10^{-9} contrast requirement	Surface deformation control to 0.1 nm rms
Stability of the point-spread function	Validation of tools at a contrast level of 10^{-9}	Validation of tools at a contrast level of 10^{-9}
End-to-end system testbeds, modeling, and simulation	Contrast $<10^{-9}$ at $<4\lambda/D$; 0.4–1 µm; Q~1, R>20%	Contrast $<10^{-9}$ for $\sim 0.6 < \lambda < 0.9$ µm at $<4\lambda/D$, Q~1
Interferometer Core Technologies		
Nulling	Stable null depth $<10^{-6}$; $\lambda \sim 7$–20 µm	Stable 10^{-6} null, covering 7–20 µm in two bands
Spatial-filter technology	Demonstrate low-loss single-mode spatial filters suitable for nulling mid-infrared light to a null depth of 10^{-6}	Single mode 50% throughput over 7 to 20 µm bandwidth
End-to-end system testbeds, modeling, and simulation	Stable 10^{-5} white light null Demonstrate detection of planets in pseudo solar system under realistic conditions.	Demonstrate detection of planets in pseudo solar system at realistic sensitivity
Structurally Connected Interferometer Technologies		
Spaceborne cryogenic structures	Closed-loop fringe tracking at room and cryogenic temperatures	Provide accurate measurements of structural and thermal stability (at cold temperature) over a frequency range from 0 to 300 Hz, consistent with closed loop fringe tracking
Modeling of large cryogenic structures	Verify modeling capability against experimental data	Models accurately predict system-level hardware performance.
Formation Flying Technologies		
Formation control algorithms	Demonstrate five-spacecraft formation flying scenarios on real-time testbed	Demonstrate five-spacecraft formation flying with interferometer simulation.
Formation sensing and metrology	Instantaneous 4π steradian field of view coverage	Demonstrate instantaneous 4π steradian field-of-view coverage functionality.
Precision formation flying	Interferometer control handoff performance level with five spacecraft. 5 cm control; 1 mm/s range-rate control; 5 arcmin bearing control; 1 km range	Demonstrate full end-to-end TPF formation flying with hand-off to the interferometer with five test vehicles controlled in six degrees of freedom
Observatory Technologies		
Cryocoolers	10 mW at 6 K; 200 mW at 18 K	10 mW at 6 K; 200 mW at 18 K

TPF Key Technologies and Development Tasks

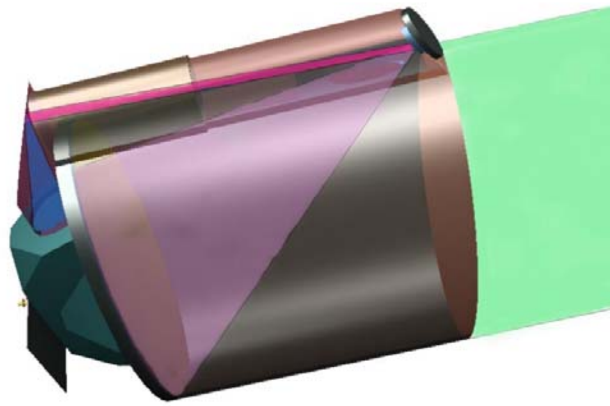
Coronagraph Technology	Development Task Where Addressed	Page Ref.
Large high-precision optics	Technology Demonstration Mirror	18
	Advanced Coronagraph Technology	30
Image and pupil-plane masks and stops	Apodized Masks and Stops Technology	24
Wavefront sensing and control	Wavefront Sensing & Control Technology	26
	High-Contrast Imaging Testbed	20
High actuator-density deformable mirror	Wavefront Sensing & Control Technology	26
	High-Contrast Imaging Testbed	20
Stability of the point-spread function	High-Contrast Imaging Testbed	20
	Industry Coronagraph Technology	22
	Tools for Integrated Modeling of Optical Systems	28
End-to-end system testbeds, modeling, and simulation	High-Contrast Imaging Testbed	20
	Industry Coronagraph Technology	22
	Tools for Integrated Modeling of Optical Systems	28
	Advanced Coronagraph Technology	30
Interferometer Core Technology		
Nulling	Achromatic Nulling Testbed	35
	Advanced Nulling Technology	42
Spatial-filter technology	Mid-Infrared Spatial Filter Technology	40
End-to-end system testbeds, modeling, and simulation	Phasing System Testbed	38
	Cryogenic Delay Line	44
Structurally-Connected Interferometer Technology		
Spaceborne cryogenic structures	Structurally Connected Interferometer Testbed	46
Modeling of large cryogenic structures	Cryogenic Structures Modeling and Technology	48
Formation Flying Interferometer Technology		
Formation control algorithms	Formation Algorithms & Simulation Testbed	54
Formation sensing and metrology	Formation Sensor Technology	56
	Thermal Shield Technology	62
Precision formation flying	Formation Algorithms & Simulation Testbed	54
	Formation Control Testbed	58
	SPHERES Flight Experiments	60
Observatory Technology		
Cryocooler technology	Advanced Cryocooler Technology Development Program	**64**

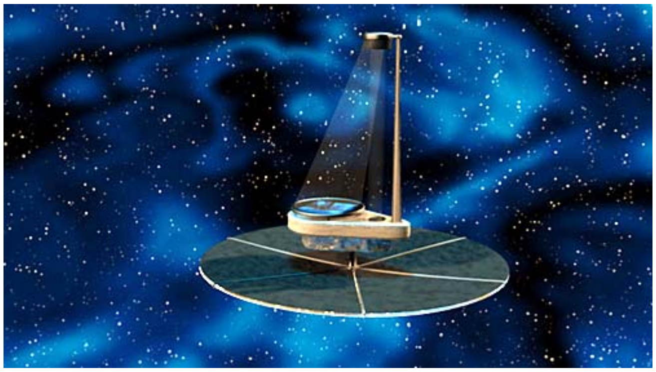
Each development task has established annual metrics covering the demonstration of key technologies over the period of FY2003 to FY2006, which will enable the evaluation of progress and ultimately the selection of the TPF mission architecture. The metrics are consistent with current understanding of the TPF key technology needs and performance goals and are intended to take the technologies to NASA TRL ~5 at the end of pre-phase A. The metrics will be further developed, updated, and/or revised as initial progress is made and evaluated and as the detailed science and performance requirements for the TPF Mission are better defined by the science and system design efforts.

For each development task, the specific need, objective, approach, scope, and assessment of current TRL are stated. Milestones, performance targets, and associated anticipated TRLs (where applicable) have been identified by year out to FY2006. The milestones represent work to be accomplished, and the performance targets are quantitative (where applicable) estimates of the level of performance that is anticipated in a given year. The nature of the planned demonstration in each area relative to understood TPF mission needs varies, but in all cases is asserted to be adequate to demonstrate TRL ~5.

Coronagraph Technology Plans

A spaceborne optical telescope with a sufficiently large diameter mirror would be capable of resolving extrasolar planetary systems and detecting Earth-like planets. A large telescope would be required to resolve Earth-like planets orbiting nearby stars, meeting the science goals of TPF. The principal difficulty in using a large optical telescope is that the faintest Earth-like planets would appear very close to their parent stars and be obscured in the diffracted starlight. High-dynamic-range imaging is nonetheless possible using telescopes equipped with high-performance coronagraphs, with specially designed optical stops and masks to either block or selectively diffract the starlight, while passing light from the planet. Using coronagraphs, images with a dynamic range of $1{:}10^5$ have been shown possible, but the detection of extrasolar Earths requires a dynamic range of $1{:}10^9$, far exceeding our current capability.





Technology Challenges and Heritage

Advances in several areas would make coronagraphs capable of detecting Earth-like planets around nearby stars. Recent studies have shown that suitably shaped or apodized telescope pupils potentially offer improvements over conventional coronagraph designs. Moreover, improvements in wavefront accuracy, especially in the mid-spatial frequencies, resulting from high-quality mirror figure combined with a high performance active wavefront sensing and control system will suppress the starlight to a level that allows the detection of planets.

Much of the technology for coronagraph-based systems will be acquired or derived from elsewhere (see p. 68). Further experience with the Hubble Space Telescope will provide a greater understanding for the control and suppression of spacecraft vibrations and low-frequency jitter, as will developments for the James Webb Space Telescope (JWST) and the Space Interferometry Mission (SIM). JWST will also provide technology advances in spacecraft systems and in large precision deployable structures suited to a visible coronagraph mission.

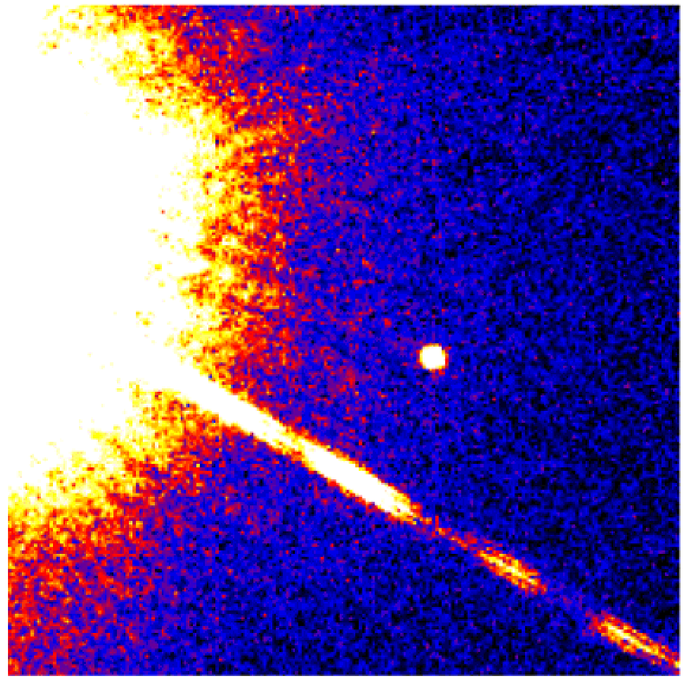
Coronagraph Technology and Testbeds

The TPF Project is developing coronagraph component and sub-system technologies and a system testbed that are necessary to determine the feasibility of a full TPF coronagraph mission.

Component and sub-system technologies under development include:

- The Technology Demonstration Mirror, which will provide a 1.8-m diameter off-axis mirror with the surface quality required by TPF and an approach to scale to the final required TPF coronagraph aperture size and mass.

- Apodizing Masks and Stops, which will be analyzed and developed to demonstrate approaches with the capability of meeting the TPF requirements. Processes and materials suitable for manufacturing masks that are stable in the space environment will also be developed.



- Wavefront Sensing and Control Technologies, including advanced algorithms and methodologies that will enable the wavefront error to be sensed with high precision, and high actuator-density deformable mirrors will be developed to control the wavefront to the necessary $\lambda/10^4$ level.

- Integrated modeling tools will be developed to provide a set of experimentally validated tools for integrated, system-level modeling of the coronagraph optical systems, including the effects of mechanical and thermal perturbations and level of control required to maintain the high stability needed for TPF.

The High Contrast Imaging Testbed (HCIT) will validate coronagraph back-end technologies and demonstrate the 10^{-10} contrast required for the detection of extrasolar planets. It will also be a facility capable of performing high-contrast observations for testing of analyses and components and alternative coronagraph concepts developed under industry and university contracts.

The industry-provided and university-provided testbed components are currently envisioned to include: analysis and fabrication of apodizing masks and Lyot stops; analyses related to wavefront propagation; error analysis and effects; improved deformable mirrors; a coronagraph front-end telescope simulator; a design for a continuous wave-front sensing system; and a design for a back-end spectrometer for sensing planet spectra. These technologies will complement the capabilities of the HCIT and lead to a flexible end-to-end TPF coronagraph testbed that can provide a platform for testing and comparing the performance of a number of specific component technologies.

Technology Demonstration Mirror

Key Technology Addressed

Large high-precision optics

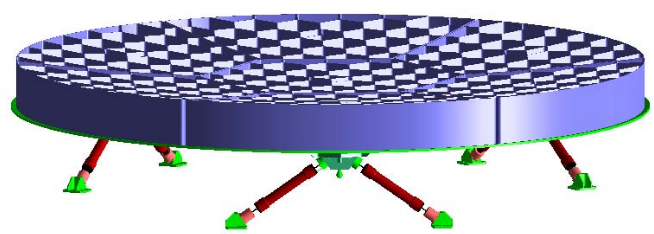
Objectives

The coronagraph designs for TPF require the fabrication of a mirror that is 4 to 10 m in its largest dimension, with very tight tolerances for the reflectivity and surface errors. The Technology Demonstration Mirror (TDM) is a 1.8-m diameter off-axis mirror that will be manufactured to demonstrate that the requirements of extremely low surface error and reflectivity variations can be met. The major technical challenge will be reducing the mid-spatial frequency surface errors on a large mirror.

Spatial Wavelength	Requirement (nm rms)	Goal (nm rms)
1 mm – 1 m (Micro-roughness)	1.0	0.5
0.1 – 2.0 cm (High spatial freqs.)	1.3	0.7
2.0 – 40.0 cm (Mid spatial freqs.)	4.8	2.4
40.0 cm and larger (Low spatial freqs.)	10.0	5.0

Approach

The TDM is being developed by industry via a two-phase competitive procurement that began in July 2002. Four companies (Kodak, Brashear, B.F Goodrich, and Tinsley) were chosen to perform 15-week studies, culminating in a Preliminary Design Review in November 2002. During the studies, the contractors worked with the TPF Project to develop detailed demonstrator concepts that would be traceable to the development of the larger TPF mirror. A technical review board met in December 2002 and advised NASA Headquarters of the recommended contractors for the second (demonstration) phase of procurements. It is anticipated that the demonstration mirror fabrication contract will extend from March 2003 to January 2006. In the final phase of the contract, the contractors will provide plans and cost proposals for developing a full-scale TPF coronagraph mirror.



Scope

- Mirror Manufacturing Process
  - Determine process effects
  - Determine materials effects
  - Understand thermal impact
  - Develop measurement and test methods to characterize surface figure
  - Understand scalability
- Coating Development process
  - Understand spatial and reflective uniformity
  - Develop coating application process and understand scalability
  - Develop method of measuring coating performance

Current State of the Art — TRL 3

The required mid-spatial frequency (MSF) performance for the TDM has not been demonstrated on the scale needed for TPF. Smaller mirrors (with a higher areal density) have demonstrated the required MSF, but in the class of the TDM, the requirement has so far been met only over part of the MSF range.

	Milestones	**Performance Targets**	**TRL**
2003	Initiate mirror demonstration contracts		3
2004	Complete mirror blank fabrication		3
2005	Complete shaping, grinding, polishing, and ion figuring of mirror	Mirror meets or exceeds spatial surface performance goals as described above	5
2006	Complete environmental test of mirror Coat and test mirror Mirror Test. Ship mirror	Mirror meets performance goals after test. Mirror meets or exceeds spatial surface and reflectance performance	5

High-Contrast Imaging Testbed

Key Technologies Addressed

Wavefront Sensing and Control, High Actuator Density Deformable mirror, Stability of the point spread function. End-to-end system testbeds, modeling, and simulation

Objectives

The High-Contrast Imaging Testbed (HCIT) is an adaptable testbed located at JPL, established to validate the high-contrast coronagraphic technology fundamental to direct detection of extrasolar planets from a spaceborne observatory. This facility is modular, allowing for integration of modules from a variety of sources, and designed for remote observing, so that users from many institutions can be supported. JPL will schedule and support guest users commencing in FY2004.

Approach

Empirical investigation/validation of core coronagraph technology is practical with HCIT. This testbed represents two essential subsystems of a hyper-contrast instrument: wavefront retrieval and correction, and coronagraphic control of diffracted light. The testbed will validate that an instrument can achieve and maintain contrast beyond 10^{-10} at the required inner working distance of the TPF coronagraph telescope. This constitutes a fundamental confirmation that phase errors can be sensed, corrected, and held for the time period of extrasolar planet detection. Furthermore, it will validate software and diffraction models necessary to construct and operate a flight instrument. The HCIT development will consist of the following hardware thrusts: continued improvement in the deformable mirror and its performance; continued demonstration of wavefront sensing and control; and testing of apodizing masks and Lyot stops provided by government, industry, and academic sources. The testbed has been designed to accommodate a suitable subscale telescope and associated masks/stops such as are planned to be developed as part of the Industry Coronagraph Technology thrust. It could be mated with a telescope containing the Technology Demonstration Mirror although considerable additional development and modification would be required beyond the currently planned scope. In addition, the HCIT can be used to correlate analyses provided by outside sources, and can accommodate possible additional back-end subsystems

Scope

- Deformable Mirror
  - Understand and improve performance
  - Improve robustness of fabrication
- HCIT system performance
  - Improve straylight performance through baffling
  - Incorporate testing of masks and stops and other components
  - Correlate performance with model predictions
  - Demonstrate performance through a variety of environmental conditions

Current State of the Art TRL 3

The testbed is in operation and has achieved contrasts of 10^{-5}.

	Milestones	Performance Targets	TRL
2003	Initiate experiments in vacuum environment with improved DM, Apodizing masks, and stray light control	Demonstrate starlight suppression to $>10^{-6}$ contrast at ~$0.6 < \lambda < 0.9$ µm at $<4\lambda/D$	3
2004	Complete vacuum environment tests continued improvement in DM technology, control of diffracted and stray light, and improved masks and stops	Demonstrate starlight suppression to $>10^{-7}$ contrast for ~$0.6 < \lambda < 0.9$ µm at $<4\lambda/D$	4
2005	Complete additional vacuum environment experiments using continually improved components. Test components from outside sources. Understand thermal impacts.	Demonstrate starlight suppression to $<10^{-8}$ with alternative optical elements (stops, masks, deformable mirrors) at $<4\lambda/D$	5
2006	Continue improving components with mask technology development and testing components from outside sources	Demonstrate starlight suppression to $<10^{-9}$ contrast for ~$0.6 < \lambda < 0.9$ µm at $<4\lambda/D$	5

Industry Coronagraph Technology

Key Technology Addressed:

Stability of the point spread function, End-to-end system testbeds, modeling, and simulation

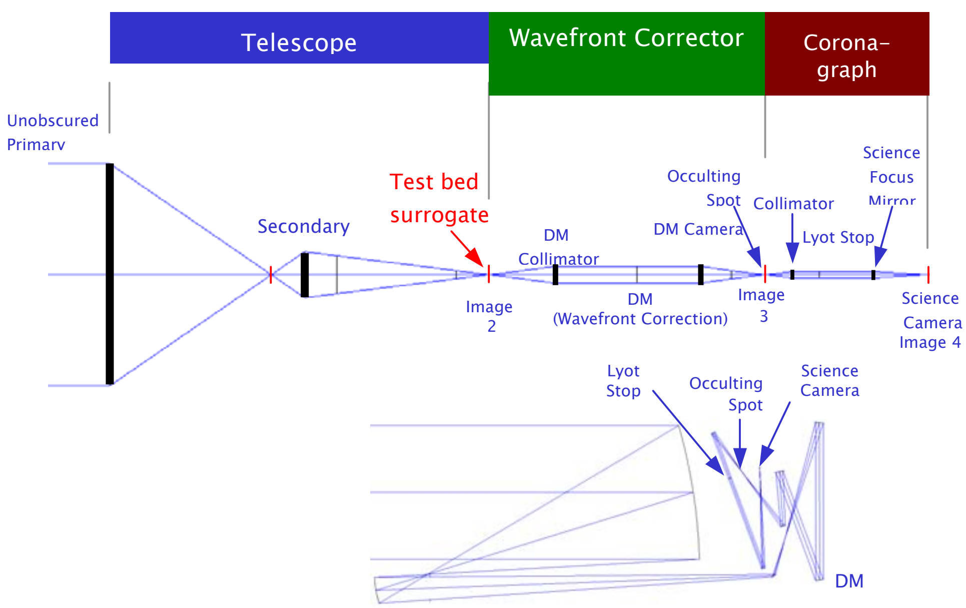
Objectives

The Industry Coronagraph Technology task will develop and demonstrate industrial capability in coronagraphic system technology through development of components and subsystems to be integrated into a testbed at JPL. This effort will develop component technologies that can function as subsystem modules in the HCIT. These developments will complement the HCIT by providing components that enhance HCIT performance or mitigate risks by providing alternative technologies or sources. The components and subsystems can either be hardware to be integrated into the HCIT for testing or analyses or code to allow modeling of components that can be included in the full system performance modeling.

Approach

Industry Coronagraph Technology will be developed through a competitive procurement process. This activity complements the HCIT, and may constitute module-level participation in HCIT, or provide analyses that complement the HCIT.

Competitive contract award(s) for Industry Coronagraph Technology will be placed in FY2003. Technologies favored for ICT development are those not specifically addressed by the High Contrast Imaging Testbed: scaled finite-conjugate telescope front ends, advanced deformable mirrors and multiplexers, pseudo-star/planet fields, wavefront-sensing instrumentation and software development, auxiliary instrumentation such as a nulling interferometer or spectrometer. Additional elements may address issues of stability, calibration, veiling glare and contamination and reflectance variance, and observing scenario optimization. Each of these topics in coronagraphic technology may be addressed by industry either through independent facilities, or under scheduled use of HCIT, bringing industry-developed modules to that facility.



Scope

- Through competitive process, award contracts to industry for:
  - Front-end telescope for HCIT (TRL 3-4)
  - Analyses and modeling tool building (TRL 1-2)
  - Develop back-end science instrument design (TRL 2-3)
  - Provide analysis and fabrication of masks and stops for HCIT (TRL 2)

Current State of the Art — TRL 2-4

The technologies developed under this task are in the early stages of development. Techniques for fabricating masks and stops with the precision required for TPF have not been well characterized. Tools for accurately modeling the optical performance also do not exist. The front-end telescope will be designed based on similar technologies, but must be designed to the particular needs of the HCIT. The back-end instrument will be based on other camera and spectrometer designs, but no instruments with comparable performance have been built.

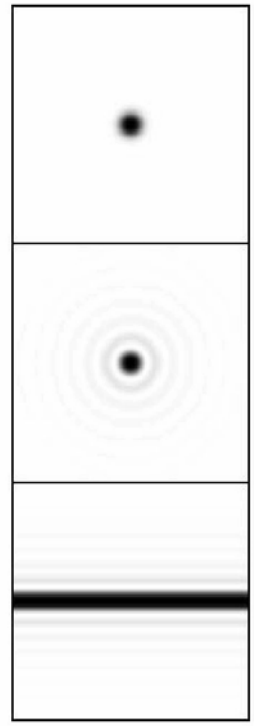
	Milestones	**Performance Targets**	**TRL**
2003	Select initial set of technology opportunities Release Solicitation Select contractors to be funded	Contracts executed.	2-3
2004	Receive initial results of analyses and studies Determine continued funding for technologies Test available components in testbed.	Delivered components and analyses integrated into HCIT and performance measured.	3-4
2005	Receive component technologies		4
2006	Deliver testbed	Demonstrate final performance.	5

Apodized Masks and Stops Technology

Key Technology Addressed

Image and pupil plane masks and stops

Objectives



The TPF coronagraph must suppress on-axis starlight, while passing light from off-axis planets that are many orders of magnitude dimmer. This activity will assure that the extremely high optical density for blocking and the uniform gradient to further smooth the signals can be manufactured to the high precision and small scale needed in the telescope image plane.

Approach

This activity will develop several concepts that demonstrate the feasibility of manufacturing apodizing occulting masks that have a very high dynamic range in optical density (OD from 0 to 8) and smooth variations within that range. Such masks are very difficult to both make and measure, and are not used in existing applications. There are two fundamental approaches to designing the mask: analog (i.e., gray scale) and binary (black and transparent). Manufacturing technology is being developed for each type of mask. JPL, universities, and industry are all anticipated to be providers of mask and stop technology. Several manufacturing techniques will be attempted for each approach. This activity will demonstrate that hardware can be manufactured to meet optical requirements in a space environment. Performance of the masks will be evaluated at JPL.

Scope

- Initiate analytic model of performance
- Compare model performance with HCIT measurements on hardware developed
- Initiate fabrication and determine:
  - Stability of materials
  - Flight-environment hardy
  - Accuracy of process
- Develop continued process improvement

State of the Art — TRL 3

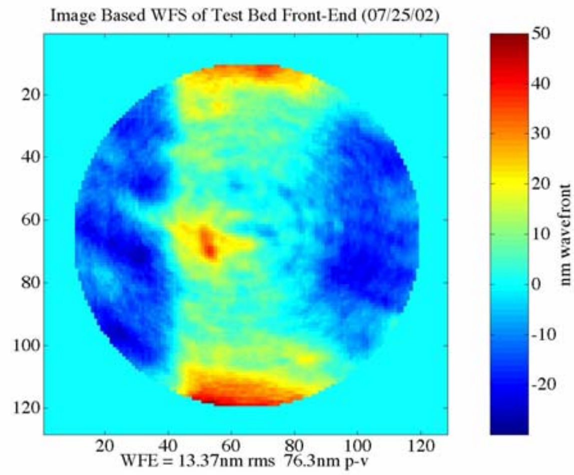
Legacy for occulting masks is primarily from unapodized ground-based coronagraphic instruments. No precedent exists for flight quality occulting masks with any combination of these requirements: apodized or band-limited design; required Optical Density of 8; very small size of ~120 µm FWHM; uniformity of ~10^6; and materials and process selection to provide stability of performance in the space environment over the experiment lifetime.

	Milestones	Performance Targets	TRL
2003	Fabrication of initial set of candidate masks Initiate analyses of binary devices	Compare performance impact of each type of mask on HCIT.	3
2004	Iterate fabrication of candidate masks based on performance results. Incorporate analysis results in fabrication processes	Performance measurements will be used to down select and/or modify fabrication processes	4
2005	Optimization of apodization functions and fabrication methods.	Receive masks consistent with 10^9 contrast requirement	5
2006	Summary report on mask design and fabrication.		

Wavefront Sensing & Control Technology

Key Technology Addressed

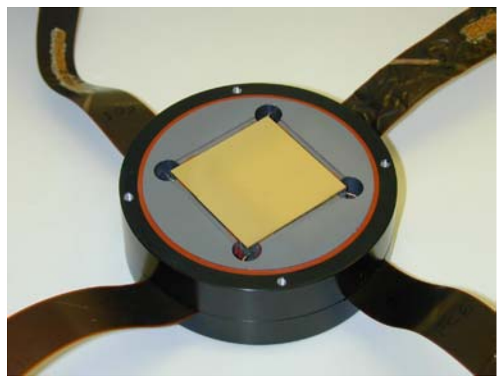
Wavefront sensing and control, High actuator density deformable mirror



Objectives

A TPF Coronagraphic imager mission will use wavefront sensing and control to correct optical aberrations incurred during fabrication and launch. The TPF Project will develop methods capable of the required extreme precision and demonstrate this performance in the lab. Long-term maintenance of wavefront quality through continuous, real-time wavefront stabilization approaches will be developed.

Approach



This activity will build on recent developments of the JWST Project in image-based wavefront sensing and control, taking that technology, validated at the sub-10^{-2} wave level, and pushing it through systematic steps to the required RMS wavefront error of less than 10^{-4} waves. This activity will also continue development of innovative wavefront sensing approaches that exploit the coronagraphic mask to measure contrast more directly. Wavefront sensing and control at the required level will be demonstrated on the High-Contrast Imaging Testbed using a high-actuator-density deformable mirror. Options for long-term stability maintenance include continuous wavefront sensing and control, using light reflected at the occulter focus, or using the science data for wavefront sensing, as well as thermal wavefront control, using heaters and thermometers to control the figure of the telescope. Optical figure maintenance using direct metrology of the telescope is another option that does not require continuous wavefront sensing.

Scope

- Correlate predictive modeling with HCIT performance
- Improve sensitivity and performance
- Demonstrate consistent, repeatable control

State of the Art TRL 3

The HCIT has demonstrated repeatable control to $\lambda/10^4$ in a laboratory environment.

	Milestones	Performance Targets	TRL
2003	Take delivery of 4096 actuator Deformable Mirror Prototype Integrate received DM into HCIT	Surface deformation control to 0.1 nm rms	3
2004	Develop and validate integrated wavefront sensing and control model	Demonstrate sensing and control to $\lambda/10^4$ in mid-spatial frequencies.	4
2005	Integrate DM and wavefront sensing and control algorithms into Engineering Model system	Demonstrate sensing and control to $\lambda/10^4$ in mid-spatial frequencies in a flight-like system.	4
2006	Refine wavefront sensing model and hardware.	Improvements in reliability, performance, or cost.	5

Tools for Integrated Modeling of Optical Systems

Key Technology Addressed

Stability of the point spread function, End-to-end system testbeds, modeling, and simulation

Objectives

Two concerns that are central to the demonstration of a TPF coronagraph are the characterization of the telescope system's point-spread function, and its stability at a contrast of 10^{-9} over long periods of time in the presence of numerous system perturbations.

The TPF coronagraph requirements necessitate development of a robust, extensible platform for multidisciplinary technology development, operating on a single, parameterized, finite element model having multi-physical attributes. The aim of this effort is not to duplicate the capabilities found across numerous commercial codes; but to achieve the level of data and process integration necessary for accurate rapid exploration of design alternatives unique to this class of problems, within a flexible framework that allows for effective capture of new technologies.

The resulting tool, developed by JPL, will be used to model components on the test bed for validation against measured performance and to model and evaluate various mission architectures.

Approach

JPL will develop code to provide a robust, extensible, and open framework for common-model method development including nonlinear heat transfer (radiation and conduction), static and dynamic structural analysis, optical aberration calculation, and design sensitivity and optimization. Additional integration capabilities (with optical analysis and control codes, for example) will be provided via high-level scripting in the Matrix Laboratory (Matlab) environment, with calls to object-level computational process modules. Though the goal is one of effectively capturing the multidisciplinary physics, it will nevertheless enable the solution of large, detailed, models (up to ~10^6 degrees of freedom) by taking advantage of efficient computational practices and by utilizing NASA Structural Analysis Program (NASTRAN)-based model descriptions, with data input extensions as required by new technologies.

Methods, new code, and models will be validated through a range of tests, from theoretical, closed-form solutions to comparison of prediction to performance on the High Contrast Imaging Testbed. Additional verification on a representative flight test case is also intended. Test architectures will also be available for participants in the Coronagraph community to model with independent tools for performance comparison purposes. This shall result in a uniquely qualified tool for coronagraphic system development.

Scope

- Common model, finite-element multidisciplinary analysis capabilities: Radiation exchange, nonlinear heat transfer, static and dynamic structural analysis, and optomechanical response computation
- Design sensitivity and optimization capabilities based on efficient approximation concepts and gradient-based mathematical programming techniques
- Correlation of methodologies and code implementation for comparison to measured performance of the HCIT

State of the Art TRL 2-3

Current "integrated" analysis requires the use of separate codes for radiation exchange, heat transfer, structural analysis, structural/optical interpolation, and optical analysis, incurring the penalties and errors associated with separate model descriptions. There is no combination of either commercial off-the-shelf and/or internally developed toolsets currently available that will allow for analysis of all multidisciplinary – structural, thermal and optical - aspects of TPF.

	Milestones	Performance Targets	TRL
2003	Continue development of structural modules and optical design tools – to alpha release level Develop and include Thermal modules to alpha release level System test case modeled to demonstrate process and to provide roadmap for design team evaluations	HCIT validation correlation of simple cases to $>10^6$ contrast accuracy prediction. Precise validation of diffraction modeling tool predictability on text-book cases	3
2004	Continued HCIT validation against simple cases. Refinement and continued development of modeling tools to beta level release	Validation of tools at contrast level of $>10^7$	4
2005	Validation of tools through comparison with other models and simplified static and dynamic analysis cases of the High Contrast Imaging Testbed. IMOS development: Gamma release	Validation of tools at a contrast level of $>10^9$	5
2006	Complete integration of tools in modeling suites. Refinement and continued development of modeling tools to gamma level release	Complete integration of tools.	5

Advanced Coronagraph Technology

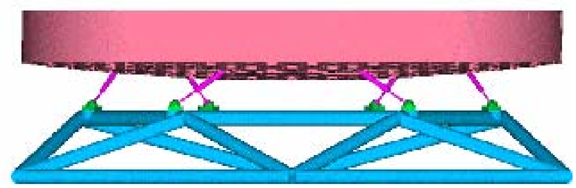
Key Technology Addressed

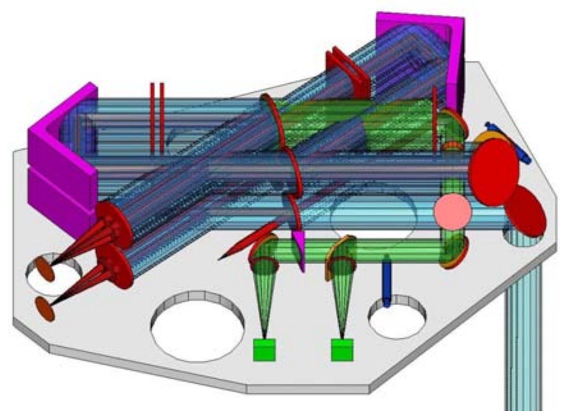
Large high-precision optics, End-to-end system testbeds, modeling, and simulation

Objectives

Investigate and develop advanced technologies that can offer breakthrough advances in the performance or implementation simplicity of coronagraph components and systems.

Approach





A number of technologies that are at very low TRL but have high potential benefits for TPF will be investigated as possible paths to performance improvements or risk reduction in the TPF coronagraph system. These technologies are in the early stages of development, and the commitment of relatively small amounts of funding to their development has the potential to return significant progress. Development for these technologies will be done at JPL and by subcontracts to industry and academia, as appropriate to each task.

As a backup to the technology provided in the Technology Development Mirror (p. 18) JPL is funding a hardware demonstration at a second vendor. In the first two years, the supplier will demonstrate 25 kg/m^2 areal density on a small-scale primary mirror using technology that can be scaled to the size required by TPF.

An alternative approach to starlight suppression in visible wavelengths is also being developed at JPL. This approach, called the visible nuller, shears the pupils in a nulling configuration, similar to that in the IR interferometer, to null the starlight collected by a single primary mirror. The nuller is followed by a coherent fiber bundle to remove wavefront errors that are not controlled by the deformable mirror. Current demonstrations are at the proof-of-concept level with a single channel, which will be scaled up to ~1000 single mode fibers, with a deformable mirror to control phase and amplitude at locations corresponding to each fiber.

Additional concepts for advanced coronagraph technology development will be solicited and considered for funding as part of the Industry and University Coronagraph Technology solicitations.

Scope

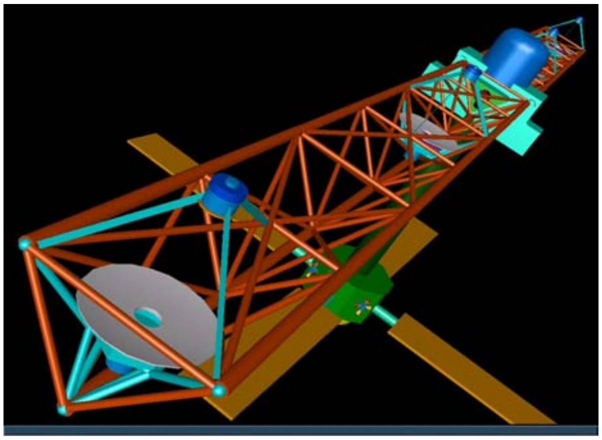
- Develop a small-scale 25 kg/m^2 primary mirror demonstrator
- Develop visible nuller to show 10^{-10} null with 30% bandwidth
- Demonstrate visible nuller imaging system with multiple fibers, and segmented deformable mirror

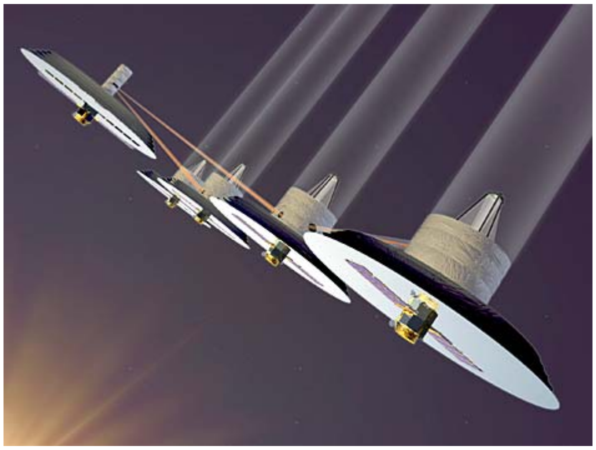
State of the Art **TRL 2**

These technologies are in the early stages of laboratory demonstration. Current level of visible nulling is demonstrated at 7×10^{-9} for a single airy spot. The visible nuller inherits technology from previous SIM related development. Further technology is acquired from current SIM metrology work.

	Milestones	Performance Targets	TRL
2003	Demonstrate starlight nulling in visible nuller	$<10^{-9}$/airy spot, single fiber	2
2004	Receive lightweighted demonstration mirror Multi-fiber imaging instrument	25 kg/m^2 areal density 10^{-10}/airy spot, multi-fiber	3 4
2005	Develop conceptual design for lightweight TPF mirror Demonstrate imaging nuller	10^{-10}/airy spot extended field of view	4
2006	Demonstrate imaging nuller in vacuum	$<10^{-10}$ contrast, 30% bandwidth, extended field of view	5

Interferometer Technology Plans





An interferometry mission, whether it is designed as an array of telescopes mounted on a connected-structure or an array of formation-flying spacecraft, would have several common features. The interferometer would operate at mid-infrared wavelengths, ~7–20 microns, to take advantage of the favorable planet/star contrast ratio and the spectral lines in that waveband. It would have telescopes ~3.5 m in diameter and be cooled to <40 K, to achieve the required sensitivity for planet detection. The mission would be launched into a 1-AU orbit, far from the Earth, to simplify the thermal design. The method of beam combination would allow the ability to chop the measurements and subtract exo-zodiacal light from the planet signal. At least two 2-input nulling interferometers, and therefore a minimum of four telescopes, would be needed. Whatever the design, an interferometer mission would require further advances in component technology, in particular for cryogenic operations and nulling, and would also need the development of systems-level testbeds to demonstrate the feasibility of such a complex system.

A structurally-connected interferometer, with its limited resolving power, would need to be at least 25–40 m long, depending on specific details of the beam combination scheme, to fulfill the goals of the TPF mission. Extending the design to structures larger than even 25 m would represent a considerable challenge for stowage, deployment, and mid-frequency stability. However, a structurally-connected interferometer would be mounted on a single spacecraft with a less complicated operations concept than the separated spacecraft version, have a constant geometry for beam transport, and could be cooled with a single thermal shield spanning the entire optical system.

The formation-flying interferometer is the most general and powerful of the nulling interferometer concepts. The longer baselines and the prospect of two-dimensional array configurations make it possible to consider deeper and more complex nulling patterns tuned to each star and extending to higher angular resolutions and longer wavelengths. However, formation flying to the necessary precision and the associated beam-transport issues remain formidable challenges.

Technology Challenges and Heritage

The technology roadmap for an interferometry mission includes heritage of precursor technology and ongoing development efforts from ground-based interferometers, including the Keck Interferometer and the Large Binocular Telescope Interferometer, and space missions such as SIRTF, JWST, and SIM. The Keck Interferometer and LBTI will provide experience with cryogenic nulling, cryogenic active optics, metrology, and many system-level concerns. From JWST and SIRTF there will be the legacy of large lightweight mirror technology, passive-cooling shield designs, and advances in detector technology. Ongoing efforts in the development of SIM will provide many of the technologies for precision relative metrology, structure design, vibration sensing and control, and space-qualified interferometry systems. The development of formation-flying technology will build on NASA's previous investments in the StarLight mission. Further input in this area will be provided by the Distributed Spacecraft Technology Program, managed through NASA Code R, which includes the development of absolute metrology sensors. The testbeds that are described in the following pages will further the necessary component technology, for nulling in particular, improve our understanding and modeling of large cryogenic structures, demonstrate an integrated formation-sensing and control system, and (most importantly) prove the viability of TPF interferometry at a system-level with end-to-end system testbeds.

Core Technology and Testbeds

Although the technology needs for mid-infrared nulling interferometers do not represent major, insurmountable challenges, considerable development at the component and system level is still required. Interferometric nulling of the light from multiple collectors over a band of ~7–20 microns is required, with stable nulls of $\sim 10^{-6}$. A major driver of system requirements is the depth and stability of the starlight null. Null depth is degraded by a number of factors such as residual wavefront aberrations, beam shear, amplitude mismatch between beams, vibration, errors in telescope pointing, polarization mismatch in the paths for each beam, stray light, and smearing due to the wavelength dependence of the fringe pattern.

End-to-end interferometer system operation is a major technical concern being addressed by the interferometry testbeds. Testing and verification of a robust end-to-end nulling interferometer will be conducted with simulated and realistic flight-like error sources. The success of these laboratory demonstrations would largely preclude the need for technology flight demonstrations and would, in Phase A, allow the initiation of the flight design with a high degree of confidence in the underlying technology.

The interferometry testbeds are aimed at retiring technology concerns and establishing feasibility of an interferometer-based planet finder in support of the 2006 architecture selection. The TPF Interferometer design team has identified the principal technical concerns and ranked them in importance. Technical concerns not retired by inheritance, or design team activities will be addressed by TPF supported technology development. The planned interferometer testbeds and technology activities are described on the following pages.

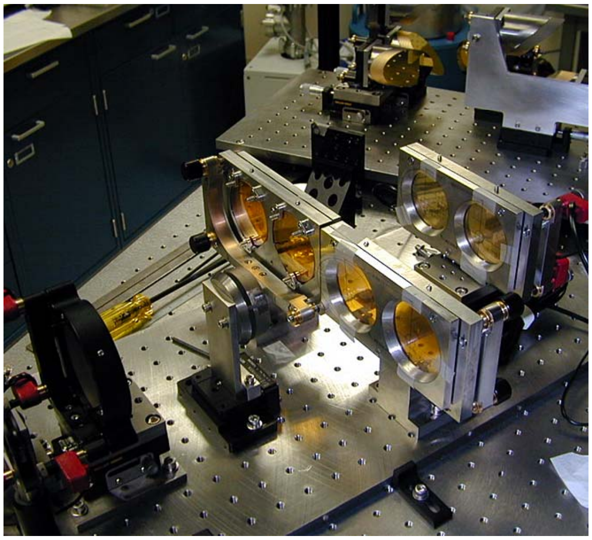
Achromatic Nulling Testbed

Key Technology Addressed

Nulling

Objectives

The achromatic nulling testbed is a sub-system testbed that will demonstrate two-beam mid-infrared nulling to a level of 10^{-6} and develop any ancillary optical components or detectors needed to achieve this level of null. The testbed will also demonstrate simple detectability of an off-axis planet while nulling the central star.



View of the TPF mid-infrared Mach-Zehnder breadboard nuller

Approach

The achromatic nulling testbed will be developed at JPL to address the optical issues related to achieving deep, broadband, dual-polarization, mid-infrared nulls. The list of technical issues and trades to be examined or developed includes field-flip vs. phase delay architectures, mid-infrared source characterization (lasers, filaments, etc.), symmetric beam injection approaches, planet injection approaches, intensity control devices, beamsplitter design, spatial filter evaluation, mid-infrared detector and camera selection, alignment algorithm development, and low-level null-control algorithm evaluation.. The detection of off-axis sources will be demonstrated with a single baseline. The goal is to develop technology that will allow the TPF spectral band to be covered by only two nullers. The proposed technical approach is to demonstrate performance of a cryo short wave (7–12 μm) nuller and to validate a model that will predict performance of a long-wave (12-20 μm) nuller. The parameters of this model will be validated, in part, by IR optical and material tests performed within the Advanced Nulling Technologies task.

Scope

- Infrared broadband nulling
- Off-axis faint source detection
- Demonstrate performance at cryogenic temperatures

State of the Art — TRL 3

Nulling interferometry has been demonstrated to 3 x 10^{-4} in thermal infrared with 30% bandwidth, and to 10^{-5} with a 10.6 µm laser. Visible light demonstrations have shown performance of 10^{-6} with a laser and 10^{-4} with stabilized visible white light of 18% bandwidth.

	Milestones	Performance Targets	TRL
2003	Validation of Modified Mach-Zehnder nuller concept - narrowband	Demonstrate 10^{-6} 10 µm laser null	4
	Validation of Modified Mach-Zehnder nuller concept - broadband	Demonstrate 10^{-4} thermal-infrared null with 25% bandwidth	4
2004	Demonstrate off-axis source detection with laser star	Demonstrate 10^{-4} off-axis source detection with strong signal	4
	Evaluate broadband nuller performance with strong signals.	Stable 10^{-5} white light null with 35% bandwidth.	4
	Mid infrared camera complete	QE 0.5, 300 Hz frame rate, read noise <3000 e^-	
2005	Validate cryogenic operation	Demonstrate 10^{-4} thermal-infrared null with 25% bandwidth	5
2006	Demonstrate ultimate white light nuller performance	Stable 10^{-6} white light null with 50% bandwidth	5
	Off axis source detection using representative star and planet photon fluxes	Demonstrate 10^{-5} off-axis source detection	

Phasing System Testbed

Key Technology Addressed

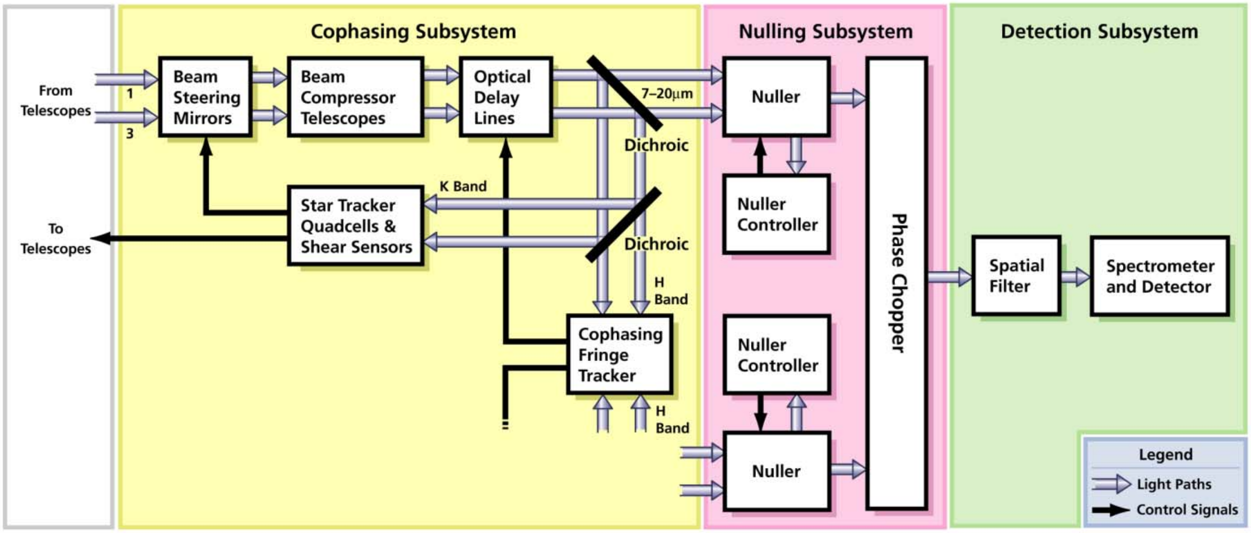
End-to-end system testbeds, modeling, and simulation

Objectives

The phasing system testbed is an extension of the Achromatic Nulling Testbed and will address issues of system complexity and techniques for system stabilization and noise suppression necessary to detect a planet.

Approach

A highly automated, four-input nulling combiner will be developed at JPL to detect a simulated star and planet system. The phasing system testbed will demonstrate the servo loops and control systems necessary for co-phasing of the four-input nulling interferometer. The emphasis will be on retiring the risks associated with system complexity and demonstration of instrument stability and noise suppression techniques (e.g., phase chopping needed to detect a planet). A combination of laser metrology and K-band fringe tracking will be developed for the pathlength control and knowledge necessary for chopping and planet detection. Fringe tracking and phasing of four starlight beams will be performed to a level of a few nm for white-light nulling. Translational motions of the separate telescopes within the interferometer entrance pupil will be simulated while fringe-tracking. Automated system alignment and pathlength control will be demonstrated. The extraction of light from a simulated planet near a bright artificial star will also be shown.



Scope

- End-to-end system test of four-beam nulling and cross-combining in the mid infrared
- Demonstration of planet detection in the presence of external, e.g. exo-zodiacal, noise sources
- Demonstration of planet detection in the presence of external and internal instrument noise sources

State of the Art TRL 2-3

Component technologies have been demonstrated.

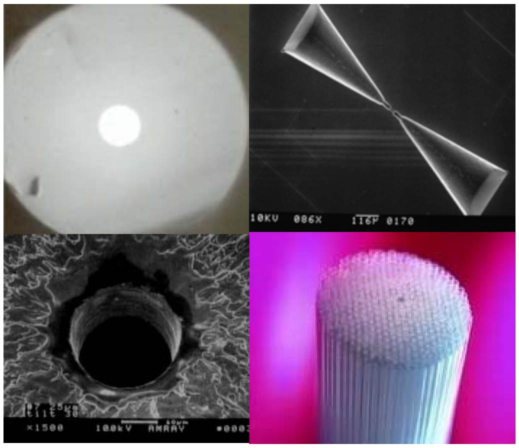
	Milestones	Performance Targets	TRL
2003	Define architectures and implementations. Complete build of development breadboard		2-3
2004	Results from development breadboard Complete build of warm phasing testbed	Pathlength control to 10 nm 4 input beams	3
2005	Demonstrate functional operation of 4-beam nuller in air Demonstrate 4 -beam nulling and co-phasing	Null depth of 10^{-4} Detection of strong planet signal (10^{-4} of star) Control of chopping to 0.1%,	4 4
2006	Demonstrate warm phasing testbed in vacuum Demonstrate detection of planet in pseudo solar system under representative conditions	Null depth of 10^{-4} Extraction of weak planet signal (10^{-7} of a laser star) Extraction of weak planet signal (10^{-6} of star in white light) Control of chopping to 0.1%,	5

Mid-Infrared Spatial Filter Technology

Key Technology Addressed

Spatial filter technology

Objectives



Spatial filters are an essential technology for nulling interferometry. Spatial filtering significantly reduces the optical aberrations in wavefronts, making extremely deep nulls possible. The most basic form of spatial filter, used in infrared nulling up until now, is a simple pinhole. The development of improved techniques for spatial filtering at mid-infrared wavelengths may be crucial to achieving null depths of 10^{-6}, making planet detection by interferometry possible. The developed spatial filters need to have a single mode throughput of at least 50% and to cover a wavelength range of 7 to 20 μm.

Approach

Spatial filters may be implemented in a variety of ways, including single-mode fiber-optics made from halogenide polycrystals or chalcogenide glasses, waveguide structures micro-machined in silicon, or through the use of photonic crystal fibers. The principal goal of this task is the development of the spatial filter technology by industry, academia, or JPL through a competitive process. This will allow the initial evaluation of candidate architectures, the infusion of development funding, the down-select to a smaller number of viable candidates, and the delivery of at least one type of working single-mode mid-infrared (7–20 micron) spatial filter at the end of the contract period.

Scope

- Broadband mid-IR spatial filter technology survey and development
- Testbed development for evaluating spatial filter performance
- Providing TPF IR Nuller Testbed with developed spatial filters

State of the Art **TRL 2**

There are no low-loss, mid-IR, single-mode spatial filters presently available. Several technologies exist that might be further developed to make the required filters, including extruded polycrystalline fibers, chacolgenide fibers, and metal-coated silicon hollow waveguides.

	Milestones	**Performance Targets**	**TRL**
2003	Contractors selected for manufacture of spatial filters		2
2004	Upgrade manufacturing facilities	10 micron single mode spatial filter technology	3
2005	Deliver phase 1 prototype to JPL	Phase 1 prototype achieves single mode operation	4
	Deliver phase 2 prototype to JPL	Phase 2 prototype achieves 50% throughput over 7 to 20 μm bandwidth	
2006	Test spatial filters from other sources	Characterize against TPF requirements	4

Advanced Nulling Technology

Key Technology Addressed

Nulling

Objectives

Investigate and develop advanced technologies that can offer breakthrough advances in the performance or implementation simplicity of nulling components and systems.

Approach

A number of technologies that are at very low TRL but have high potential benefits for TPF will be investigated as possible paths to performance improvements or risk reduction in the TPF nulling system. These technologies are in the early stages of development, and the commitment of relatively small amounts of funding to their development has the potential to return significant progress. Development for these technologies will be done at JPL and by subcontracts to industry and academia, as appropriate to each task.

Current baseline design calls for covering the 7–20 μm TPF observation spectrum with two or more sets of bulk-optics nullers, each dedicated to a certain spectral region. IR Optical Materials and Coatings will procure beamsplitter and optics materials and coatings from various industry and university sources that will enable one or two nullers to cover the entire observation spectrum. This will include investigation of coatings and materials issues necessary for cryogenic operation. The goal is to design a beamsplitter that is sufficiently symmetric to replace the dual-beamsplitter MMZ approach with a single beamsplitter in a given nuller.

To null the interfering beams to the levels required for TPF, the input beams' wavefront, polarization, and intensity must be matched to very high levels. The Adaptive Nuller is a device concept under development at JPL that that will actively correct for wavefront, intensity, and polarization imperfections of the beams entering the nuller and therefore will greatly reduce the performance requirements on the entire optical beam train of the interferometer.

The integrated optics (IO) task will investigate the possibility of replacing current bulk optics nullers with a set of integrated optics nullers. Integrated optics implementation would greatly reduce the weight, size, and complexity of the nuller and would dramatically improve its stability. This work will be done at the University of Arizona, in close collaboration with JPL.

Additional concepts for advanced interferometer technology development will be solicited and considered for funding as part of the Industry and University Coronagraph Technology solicitations.

Scope

- Adaptive Nuller
- Integrated Optics
- Symmetric Beam Splitter
- IR Optical Materials and Coatings

State of the Art — TRL 2-3

The technologies included in this technology development task are all in the early stages of development.

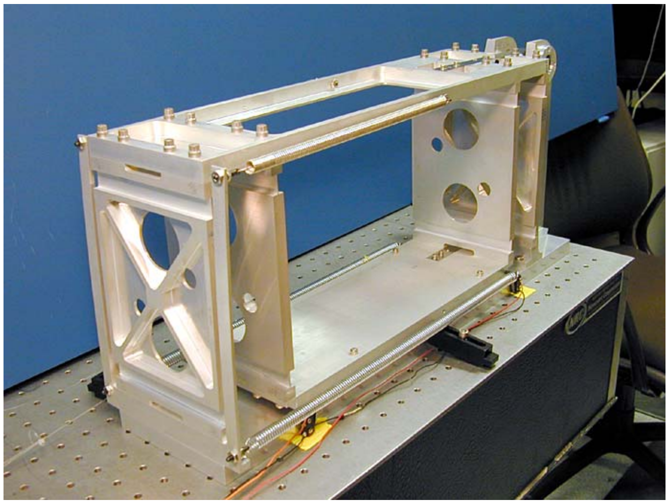
	Milestones	Performance Targets	TRL
2003	Initial Integrated optics models	Modeled to function at 10 µm	2-3
	Award symmetric beamsplitter university contract		
2004	IO beam combining prototype delivered	10 µm operation	3
	Adaptive Nuller proof of concept validation	Operation at visible wavelengths	
	Deliver prototypes of IR components	Broadband performance within 7–20 µm range at room temperature	
	Delivery of symmetric beamsplitter	8 to 14 µm bandwidth	
2005	IO nulling combiner prototype delivered	10 µm operation, 10^{-2} null depth, 10% throughput	4
	Adaptive nuller mid infrared validation	MIR polychromatic dual-polarization control	
	Deliver next generation prototypes of IR components	Narrowband operation at cryogenic temperatures	
2006	IO Delivery of two beam IR nuller	Two-beam nuller, 5×10^{-5} null depth with 20% bandwidth at 10 µm	
	Deliver final prototypes of IR components	Broadband performance within 7–20 µm range at cryogenic temperatures	4

Cryogenic Delay Line

Key Technology Addressed

End-to-end system testbeds, modeling, and simulation

Objectives



Delay lines provide the pathlength compensation that makes the measurement of interference fringes possible. When used for nulling interferometry, the delay line must control pathlengths so that the null is stable and controlled throughout the measurement. This activity will develop a low noise, low disturbance, high bandwidth optical delay line capable of meeting the TPF interferometer optical path length control requirements at cryogenic temperatures. A prototype device will demonstrate performance features that give confidence in the ability to satisfy flight performance requirements.

Approach

Cryogenic testing and characterization will be completed on an optical delay line prototype that was designed and fabricated by JPL under prior funding. The knowledge gained plus new TPF requirements from the interferometer architecture and design teams will be inputs to a redesign for a next generation cryogenic optical delay line. The new design will resolve tradeoffs as to the number of articulation stages, actuator/sensor selection and optical prescription. Magnetostrictive actuators are may be used for fine stage control due to their being relatively insensitive to performance losses at cryogenic temperatures. Following redesign and fabrication, the new delay line will be tested and characterized at both room and cryogenic temperatures. Limited design improvements may be implemented based on discoveries from testing and as permitted within funding constraints.

Scope

- Develop technology for Interferometer OPD control at cryogenic temperatures.
- Implement and test prototype system at 77K in lab.
- Deliver prototype delay line, documentation of performance and design to Program

State of the Art — TRL 3

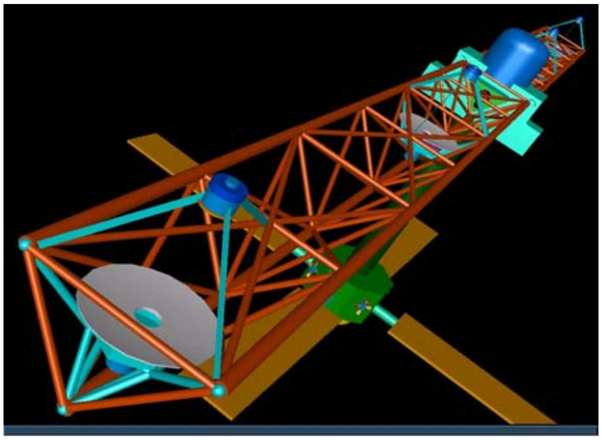
Delay lines at room temperature for 10 nm control vibration and vacuum tested (TRL 6). There has been little development for cryogenic operation.

	Milestones	Performance Targets	TRL
2003	Operate prototype closed-loop at 77K	20 nm rms OPD static, 1 cm/sec slew open loop	3-4
2004	Next generation delay line fabricated	Open loop pathlength jitter measurement at nm-precision from 0 to 2000 Hz	4
2005	Operate prototype closed loop at room temperature	3-4 nm rms OPD at room temperature	4
2006	Operate prototype at closed loop at 77K	3-4 nm rms OPD at cryogenic temperatures.	5

Structurally Connected Interferometer Testbed

Key Technology Addressed

Spaceborne cryogenic structures, End-to-end system testbeds, modeling, and simulation



Objectives

The objective of the Structurally Connected Interferometer Testbed is to provide valuable experimental information applicable to mid-IR nulling interferometers on large, spaceborne, cryogenic, deployed structures by characterization of their vibration response and thermal stability. Dynamic and thermal stability measurements at the nanometer level on structures scalable to 25 to 40 meters in length and at temperatures traceable to <40 K will improve our ability to predict performance of TPF-class structures.

Approach

Large deployable cryogenic structures technology will be acquired through industry contracts. The Structurally Connected Interferometer Testbed will be developed through a two-phase procurement process. Multiple contractors will be selected to design the testbed up to the Preliminary Design Review, and the most viable concept will then be selected for further development and demonstration by 2006.

At a minimum, measurements of structures, of ten or more meters in length, will be made to determine or predict their structural vibration characteristics, temporal and thermal stability, jitter, damping, and component (e.g., hinge/latch) behavior at cryogenic temperatures. These measurements will be used to improve the modeling of even larger structures and to clarify the trades between the designs of structurally connected and formation-flying interferometers. The full scope of these testbeds will be determined based on proposals from industry following an initial study phase and may incorporate additional validation through the use of a simplified interferometer beam train with fringe-tracking capability.

Scope

- Characterization of the dynamic and thermal stability of large structures
- Performance error budget for interferometer structures
- Hinge/latch characterization

State of the Art TRL 3

The SIM project is developing ten-meter class non-deployable structures that are stable to 1000 nm and operate near room temperature.

	Milestones	Performance Targets	TRL
2003	Contract start – study phase		3
2004	Contract start – demonstration phase		
	Design and fabricate component test hardware	Accurate measurements of structural and thermal stability to nanometer precision (both warm and cold) over a frequency range from 0 to 300 Hz	3-4
2005	Characterize components (e.g., hinge/latch) at warm and cold temperatures	Accurate measurements of structural and thermal stability (at room temperature) to nanometer precision over a frequency range from 0 to 300 Hz	4
	Complete fabrication and assembly of testbed hardware		
	Characterize testbed hardware at room temperature		
2006	Characterize testbed hardware at cold temperature	Accurate measurements to nanometer precision of structural and thermal stability (at cryogenic temperature) over a frequency range from 0 to 300 Hz	5

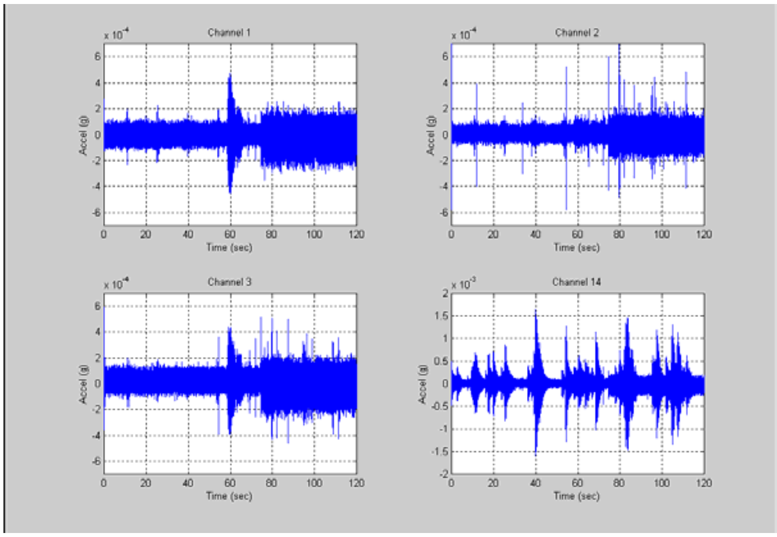
Cryogenic Structures Modeling and Technology

Key Technology Addressed

Modeling of large cryogenic structures

Objectives

The stability and vibration characteristics of interferometer support structures must be shown to meet the requirements of nulling. This task will provide accurate mechanical models for predicting the zero-g behavior of a structurally-connected interferometer at cryogenic temperatures. Component level testing will be performed to validate models at cryogenic temperatures. System-level structural models will be validated where possible using experimental data provided by the Structurally Connected Interferometer Testbed.



Approach

Accurate models will be developed at JPL for predicting the nanometric structural stability and damping of interferometer structures, including nonlinear and microdynamics effects. Of particular concern is the physics of materials and frictional interfaces at cryogenic temperatures. Standard linear representations of structures cannot adequately represent these effects, and new modeling approaches will be investigated. The modeling will include deployment mechanisms, and structural sub-assemblies, as well as the long primary truss. Tests will be performed at cryogenic temperatures using high precision metrology systems to characterize the nanometric stability of mechanisms with progressively more complex designs, starting with materials and culminating in component sub-assemblies of flight-like hardware. System-level structural data will be provided by the Structurally Connected Interferometer Testbed. The test data will validate the modeling approach, and new models will be used to investigate the need for active/passive disturbance-isolation systems. The structural models will be integrated within end-to-end models developed for the Integrated Modeling of Optical Systems (IMOS) software environment.

Scope

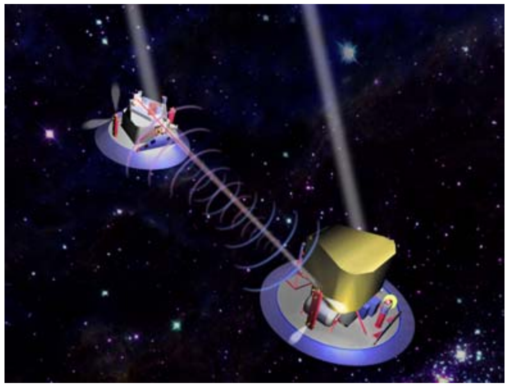
- Modeling of hinges and latches at cryogenic temperatures to nanometer precision
- Test hardware components and compare to models
- Validate system models using Structurally Connected Interferometer testbed provided data.

State of the Art TRL 3

Preliminary models and tools exist but have not yet been validated at the levels and environments required by TPF.

	Milestones	Performance Targets	TRL
2003	Deliver preliminary model forms Create generic cryo/nano test plans		3
2004	Develop pretest component models Perform cryo tests on simple frictional interfaces and subassemblies	Models accurately predict physics of friction at cryogenic temperatures	4
2005	Complete component models and validate against component test data Perform cryo tests on flight-like hinge/latch	Models accurately predict component hardware performance at cryogenic temperatures.	4
2006	Update system models to match further system level hardware development on the structurally connected interferometer testbed	Models accurately predict system-level performance of structurally connected interferometer testbed.	5

Formation Flying Technology and Testbeds



The principal objective of formation flying is to control the relative locations of the separated spacecraft so that the beams of starlight that are sampled by each telescope travel the same distance to the beam combiner. At the combiner, each optical beam will have its own delay line, with tens of centimeters of adjustable delay, and thus the separated spacecraft need only be controlled in their relative positions at a level of several centimeters. Fringes can then be found on each baseline using a multi-stage pathlength servo with piezo-electric transducers, or equivalent, to provide nanometer-level control.

The formation-flying array will be launched into an orbit far from the Earth, and on-board autonomy will be essential. Multiple spacecraft in a formation necessitates a distributed architecture for relative sensing, communications, and control; each spacecraft in the formation must sense the relative location of its neighbors and relay this information to each of the other elements. A hierarchical and distributed precision formation control algorithm is needed to guide the maneuvers. The maneuvers must also be orchestrated to conserve and balance the consumption of propellant amongst the elements in the array. The overall formation system architecture needs to support a high degree of system robustness. Specialized abilities, such as "lost-in-space" formation acquisition and collision avoidance, must be designed into the control algorithms to make the system fault-tolerant and to avoid a catastrophic mission failure.

The formation flying capability also depends critically on autonomous on-board relative sensing of the location of other spacecraft in formation. The formation sensor suite on each spacecraft, which consists of multiple sensing stages, provides this critical capability. The acquisition sensing stage will cover the broadest field-of-view, though with the least accuracy. It will enable acquisition of the formation, provide collision avoidance, and prevent drifting of spacecraft away from the formation. The medium sensing stage will provide refinement of the relative knowledge and enable acquisition and lock of the fine sensing stage. The fine sensing stage in turn will enable precise and stable control of the whole formation for acquisition of science target stars, fringe acquisition and tracking, and planet detection.

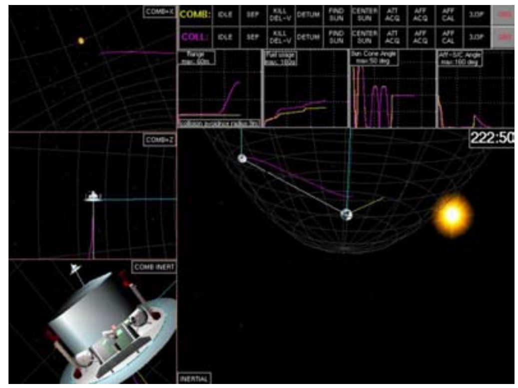
Formation Flying Technology Heritage

TPF will benefit tremendously from the ~$75M investment NASA has made over the last several years in formation flying technology as part of the StarLight Project. This effort, now incorporated into the TPF Project, demonstrated significant progress in component, assembly, sub-system and system level technology demonstration for a precision formation flying interferometer in space. The top-level performance requirements for the StarLight mission met or approached anticipated TPF requirements in a number of key areas. At the completion of the StarLight Project, four significant technology milestones were achieved which form the basis upon which the TPF Formation Flying Interferometer technology plans have been developed.

Autonomous Formation Flying (AFF) Sensor

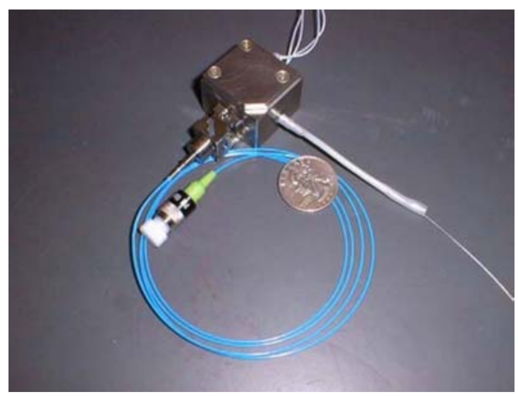
A Ka-band prototype of the AFF Sensor was developed and is fully functional. End-to-end system functionality has been verified through laboratory testing and operation on the 385m JPL Outdoor Test Range (top figure at right). Performance of fundamental algorithms has been verified in a distributed spacecraft environment. Performance dependence upon the spacecraft architecture is understood. Results show that the AFF Sensor can meet the StarLight performance requirements in estimation of the range (2 cm) and bearing angles (1 arc-minute), while providing a moderately wide field-of-view (±70 degrees).

Formation Flying Control Simulation



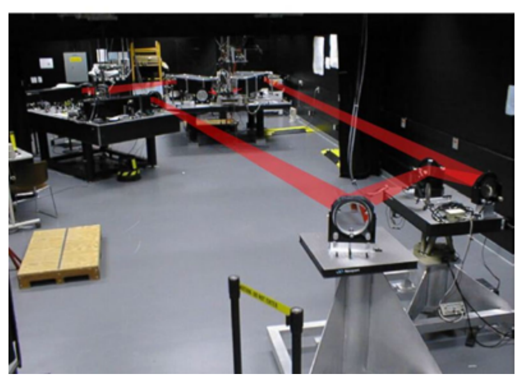
A high fidelity closed loop formation controls simulation testbed was developed for the Starlight two-spacecraft architecture (second figure at right). Control algorithms were developed and demonstrated for formation acquisition, collision avoidance formation maneuvering, formation control, and observation on-the-fly. Simulation results show that the formation control performance could meet the StarLight requirements of 10 cm and 1 mrad.

Precision Metrology Sensors



A prototype long range (600 m) dual-target laser metrology system was developed for the StarLight mission based on a ruggedized 1.32 µm space-qualifiable laser (third figure at right). Laboratory results show that the system could meet the StarLight mission requirements. Sensitivity to 1 µm offset with precision of 11 pm over a 600 m range has been demonstrated in the laboratory.

Formation Interferometer Testbed (FIT)



One of the challenges for a formation flying interferometer is to acquire and stabilize an optical system distributed over unconnected moving platforms. The StarLight mission technology development team accomplished this for the first time anywhere. The Formation Interferometer Testbed (bottom figure at right) demonstrated fringe acquisition at > 40 µm/s relative collector/combiner motion in the interferometer plane (both radial and transverse directions) and fringe lock for at least 10 seconds at relative rates of up to 30 µm/s, velocities typical of interspacecraft motion in the formation.

Formation Flying Testbeds

The formation-flying testbeds described in the following pages build on the success of the StarLight efforts and cover the full suite of technologies for TPF formation flying that need to be developed and demonstrated in a ground-technology program prior to the 2006 architecture selection. The testbeds described here will establish the viability of the formation-flying mission architecture for the TPF, while retiring and mitigating mission risk. The development and demonstration of the requisite formation-flying technologies are organized within a series of ground testbed activities as follows:

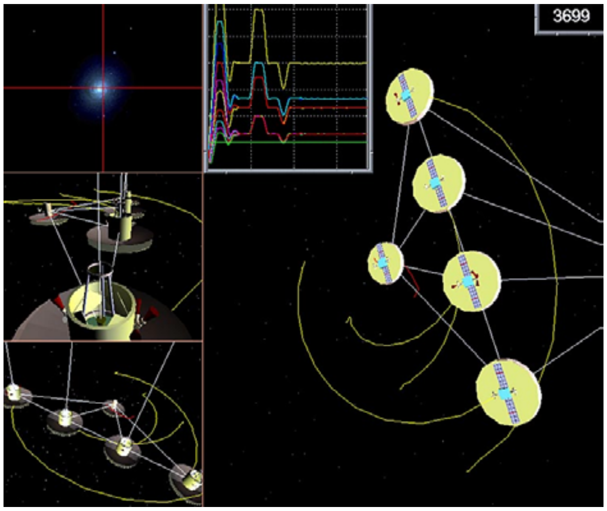
Testbed	**Capability Demonstrated**
Formation Algorithms & Simulation Testbed (FAST)	End-to-end formation flying simulation in a distributed real-time environment
Formation Sensor Technology (FST)	Large-angle articulated 4π steradian formation acquisition hardware demonstration
Formation Control Testbed (FCT)	End-to-end validation of formation flying algorithms in a realistic multi-vehicle dynamic hardware testbed
SPHERES Flight Experiments	TPF representative formation maneuvers
Thermal Shield Technology	Characterize impact of material on RF sensor performance

These testbeds are complementary in addressing the technology concerns for the overall formation flying system. Each testbed will not only develop and demonstrate new technology, but will also deliver a performance error budget validated by experimental results. FAST will demonstrate the end-to-end formation flying for a five-spacecraft TPF formation in a distributed realtime software simulation. FST will provide hardware demonstration of the formation acquisition sensor, verifying the instantaneous 4π-steradian field-of-view coverage required for initial acquisition of the formation. It will also provide sensor models assumed in the FAST formation flying system and FST. FCT will demonstrate key TPF relevant mission scenarios, including aspects of formation acquisition, collision avoidance, and observation-on-the-fly maneuvers in an autonomous ground testbed. It will also implement and validate algorithms developed in FAST. SPHERES experiment will provide lessons-learned for formation flying. The thermal shield testbed with be used to characterize the impact of different thermal shield materials on the RF sensor performance.

Formation Algorithms & Simulation Testbed

Key Technology Addressed

Formation control algorithms, Precision formation flying



Objectives

Formation-flying interferometry will require sophisticated new algorithms for the simultaneous control of multiple spacecraft. The Formation Algorithms & Simulation Testbed provides a high-fidelity end-to-end software-simulation environment to demonstrate realistic mission scenarios of formation-flying interferometers, including formation acquisition, formation calibration, formation maneuvering, re-configuration, and nominal observation.

Approach

Phased development at JPL, expanding on results from StarLight, is planned to yield a distributed real-time simulation demonstrating nominal operation in the first two years, followed by further development to thoroughly address issues in off-nominal and instrument operation in the following years. FAST-developed algorithms will also be verified with hardware in the loop in the Formation Control Testbed, which will use a common architecture to maximize portability.

The work will include development and integration of: formation control architecture and algorithms; high-fidelity models for spacecraft dynamics, actuators, and sensors (from the Formation Sensor Testbed); high-fidelity models for interspacecraft communication, instrument operation, and ground commanding and monitoring; and a distributed real-time, simulated flight-like execution environment for an end-to-end real-time simulation of the formation flying system. The distributed formation control, sensing and communication architecture will be developed to maximize system robustness.

Scope

- Development of FF control architecture and algorithms for a five-spacecraft TPF mission
- End-to-end demonstration of TPF FF performance and robustness in a high-fidelity distributed real-time simulation testbed
- Validation of FF control architecture and algorithms using the FCT hardware testbed.

State of the Art — TRL 3

Formation flying algorithms have been designed and simulated for the two-spacecraft StarLight mission, including those for initial formation acquisition, formation collision avoidance, path planning, and nominal control including observation on-the-fly scenarios.

	Milestones	Performance Targets	TRL
2003	Implement StarLight two-spacecraft formation flying algorithms into the real-time distributed environment.	Demonstrate *two*-spacecraft autonomous formation flying with 5cm range and 5arcmin bearing control.	3-4
2004	Implement new five-spacecraft formation flying algorithms into the real-time distributed environment.	Demonstrate *five*-spacecraft nominal formation flying with 5cm range and 5arcmin bearing control.	4
2005	Exercise off-nominal scenarios in the real-time distributed environment. Validation of 2 spacecraft algorithms by Formation Control Testbed	Demonstrate five-spacecraft off-nominal formation flying scenarios. 2 spacecraft algorithms, 5 cm range 5 arcmin bearing	5
2006	Acquisition of the optical metrology system. Validation of 4 spacecraft algorithms by Formation Control Testbed Validation of 5 spacecraft algorithms by Formation Control Testbed	Demonstrate five-spacecraft formation flying with interferometer simulation, 10 arcsecond RMS metrology bearing knowledge 5 cm range, 5 arcmin bearing 5 cm range, 5 arcmin range	5

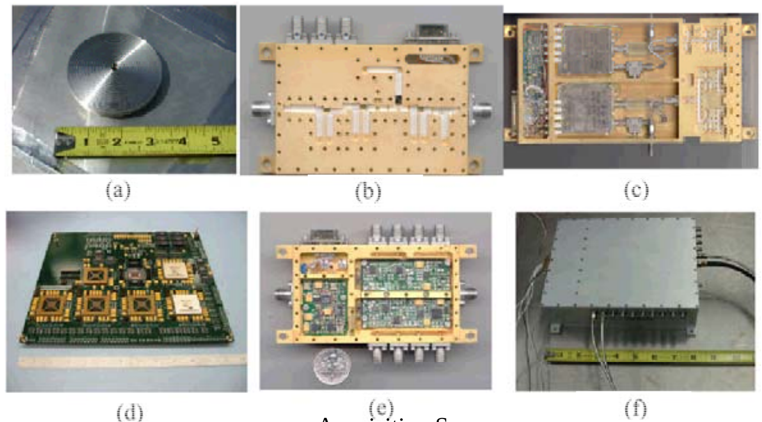
Formation Sensor Technology

Key Technology Addressed

Formation Sensing and Metrology

Objectives

Formation-flying interferometry will require the development of a suite of sensors to enable formation acquisition, stabilization, and precise control to allow fringe acquisition and tracking. The formation sensor suite may consist of multiple sensing stages, namely: acquisition (coarse), handoff (medium), and track (fine) stages. Each finer stage provides higher precision with a narrower field of view. The Formation Sensor Testbed (FST) will develop and demonstrate the key technologies required for the formation sensor suite.



Acquisition Sensor
Prototype Hardware

Approach

The Formation Sensor Testbed will focus on demonstrating the performance of the formation acquisition sensor. The Autonomous Formation Flying (AFF) sensor, developed for StarLight, will be enhanced for use as the acquisition sensor. A 60 MHz baseband processor, started under StarLight, will be delivered to the FST to extend the signal processing capability of the RF sensor architecture. A new signal structure will be developed to allow the sensor to operate simultaneously on multiple spacecraft, to implement passive radar operation for added robustness against collision avoidance, and to eliminate the need for time-consuming maneuvering during initial formation acquisition by resolving carrier cycle ambiguities in the differenced phase for the bearing-angle measurement. Existing RF transceivers as well as software inherited from StarLight formation sensor design will be modified for prototype system development and demonstration.

The prototype formation acquisition sensor will be developed and demonstrated at JPL in the indoor testbed and the outdoor articulated testbed to demonstrate the sensor overall function and performance. The indoor testbed will be used for software development, hardware and software integration and test, end-to-end functional verification, and performance model validation excluding multipath error. The outdoor articulated testbed will be developed to validate end-to-end performance including the error contribution from multipath.

Scope

- 4π steradian acquisition sensor design and performance analysis
- Demonstrate functionality of acquisition sensor across three spacecraft in indoor functionality testbed
- Demonstrate instantaneous 4π steradian field-of-view coverage and performance of the acquisition sensor across three spacecraft in an articulated outdoor testbed

State of the Art — TRL 3

Significant progress has been made in developing the formation sensors for two-spacecraft operation, as demonstrated by the Ka-band Autonomous Formation Flying (AFF) sensor, and Laser Metrology in the StarLight technology program, and LAMP/LADAR in the Mars technology program. However, very little effort has been made on a robust formation acquisition sensor needed by TPF formation mission. To meet the TPF formation mission needs, the Formation Sensor Testbed (FST) will develop and demonstrate the key technology of the acquisition sensor at this time. In the long run, the remainder of the sensor suite needs to be evaluated and the integrated sensor suite be demonstrated. This is not currently in the scope of this testbed.

	Milestones	Performance Targets	TRL
2003	Complete AFF baseband processor Demonstrate bearing measurement.	Demonstrate 60 MHz operation Demonstrate 3 degrees bearing angle accuracy with no maneuvers required for bearing angle ambiguity calibration. 5 degree without spacecraft calibration maneuver	3-4
2004	Implement the end-to-end functionality prototype system.	Demonstrate 50 cm range and 1 degree bearing measurements excluding error from multipath.	4
2005	Complete outdoor testbed demonstration	Demonstrate 50 cm range and 1 degree bearing measurements excluding error from multipath. 4π instantaneous coverage	4-5

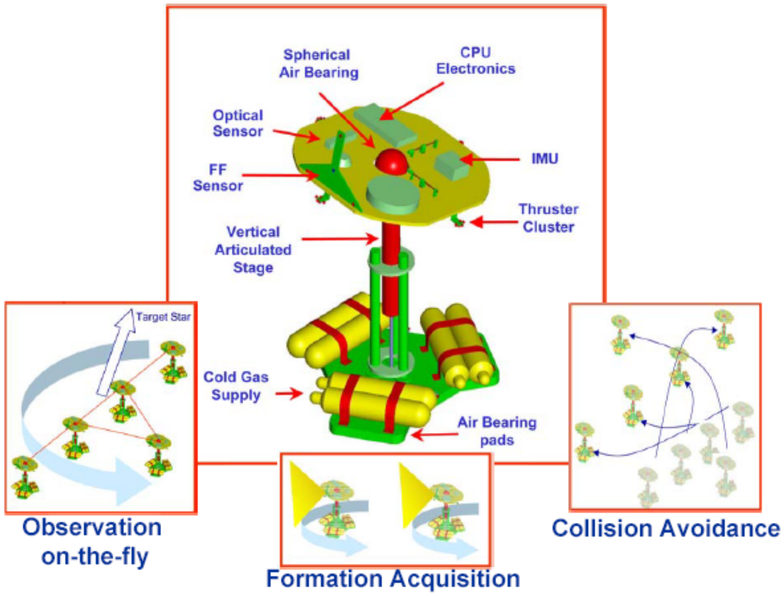
Formation Control Testbed

Key Technology Addressed

Precision formation flying

Objectives

The Formation Control Testbed will demonstrate an end-to-end autonomous formation flying system in a 1-g environment. It will emulate real spacecraft dynamics and validate formation-flying algorithms using multiple mobile test vehicles within a ground-based laboratory to provide a realistic flight-like end-to-end demonstration. As an integrated test environment, FCT provides a system level verification and demonstration capability for key component technologies of algorithms from FAST and formation sensing from the FST.



Approach

The Formation Control Testbed will be a ground-based laboratory consisting of five test vehicles, procured through subcontracts and integrated at JPL, emulating TPF formation. FCT will demonstrate formation acquisition, TPF-like formation maneuvering, and operations using the formation algorithms developed in the FAST. Sensors developed under the FST will be integrated and demonstrated in the FCT where feasible. FCT will validate the FAST algorithms and formation flying architecture. To emulate the real spacecraft dynamics, the testbed design will have realistic spacecraft-like dynamical behavior, mobility, and agility using linear and spherical air-bearings, so that control is demonstrated in five full degrees of freedom and a sixth with limited range. With such dynamical and functional similarity to the TPF spacecraft, the FCT will provide direct emulation of spacecraft behavior with thruster and reaction-wheel based actuation, and direct relative sensing of the resulting motion with the on-board formation sensors. These architectural, functional, and dynamical similarities between the FCT and the TPF will provide a direct migration path of the FCT validated integrated formation system to the TPF flight system.

Scope

- End-to-end multi-vehicle formation flying ground hardware testbed
- Demonstration and validation of FF architecture and algorithms
- Common sensing, communication, and formation control architecture with TPF mission.

State of the Art **TRL 3**

No single testbed demonstrating end-to-end autonomous formation flying in a space representative dynamic environment exists.

	Milestones	Performance Targets	TRL
2003	Formulation, architecture, design of Formation Control Testbed Robot #1 delivered by vendor	Robot #1 operational	3
2004	Formation flying demonstration with 1 robot Formation flying demonstration with 2 robots	5 cm / 5 arcmin accuracy	4
2005	Formation flying demonstration with 4 robots	5 cm/5 arcmin accuracy	5
2006	Formation flying demonstration with 5 robots and handoff to interferometer metrology	10 arcsec rms bearing accuracy.	5

SPHERES Flight Experiments

Key Technology Addressed

Precision formation flying

Objectives

The SPHERES satellite formation flight laboratory, developed by DARPA and MIT for the Orbital Express program, is scheduled for 8 months on the International Space Station after delivery in June 2003. One-eighth of the SPHERES on-orbit resources are available to the TPF program for testing of formation-flying algorithms within the risk-tolerant, controlled, microgravity environment of the International Space Station.

Approach

The SPHERES testbed consists of three small self-contained vehicles, each equipped with sets of ultrasonic and infrared transmitters and receivers. The position and attitude of each vehicle are controlled by a set of twelve cold-gas thrusters. Formation maneuvers, representative of TPF mission scenarios, will be implemented for testing on-board the International Space Station. This could include array rotation maneuvers where two or three SPHERES are oriented in a line at equal spacing with the array rotated about its center of mass and re-pointed in various directions, simulating the observation of several science targets. The recovery from a "lost-in-space" scenario with several satellites might also be tested. Various array reorientation procedures and complex maneuver sequences representing the observation of several science targets will be tested as resources permit. The possibility of a reflight of an up-graded version of SPHERES will be investigated.

See also: http://ssl.mit.edu/spheres/

Scope

- Three-vehicle demonstration of autonomous formation flight
- Operates inside the International Space Station
- Six degrees of freedom per vehicle

State of the Art — TRL 4

At this time, no single testbed demonstrating 6 degree-of-freedom end-to-end autonomous formation flying in a representative micro-gravity environment exists. Breadboard demonstrations have been performed in the KC-135 zero-gravity environment.

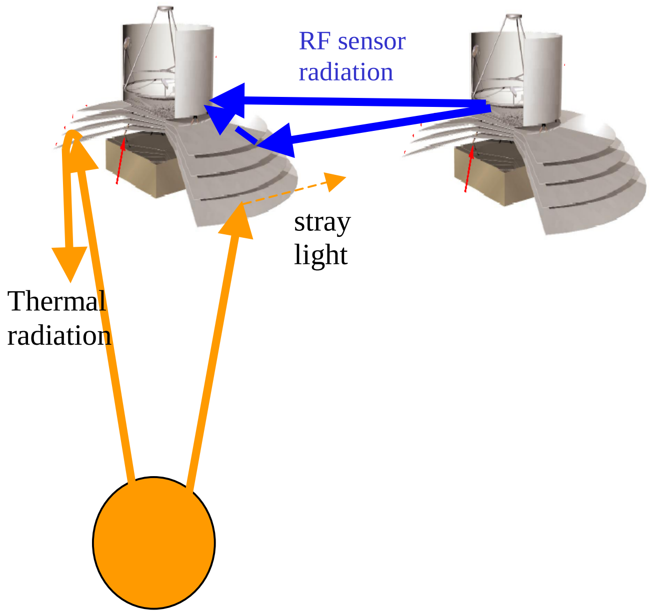
	Milestones	Performance Targets	TRL
2003	Launch and perform experiments in the International Space Station.	Demonstrate autonomy and control algorithms for TPF representative maneuvers.	6
2004	Deliver final report	Conclude successful demonstration of the TPF-representative maneuvers.	6

Thermal Shield Technology

Key Technology Addressed

Formation sensing and metrology

Objectives



The TPF Formation Flying Interferometer concept requires a thermal shield that has multiple requirements. Thermal performance requirements must be satisfied in addition to satisfying other concerns such as material choices for the shield related to RF multi-path and diffraction, mitigation of stray light on the edge of the thermal shield, and deployment of the thermal shield. The Thermal Shield Technology task will address these technical concerns.

Approach

The Thermal Shield technology task will mitigate the concerns related to RF multi-path and RF diffraction off the thermal shields in a separated spacecraft TPF. Many issues related to RF multi-path and diffraction can be solved by careful design of the thermal shield and sensor placement that is performed by the TPF Design Team. By delaying the start of the Thermal Shield task by one year, it is possible that this aspect of the Testbed will not be necessary. If it is found to be necessary, the Thermal Shield Testbed will characterize materials and perform a demonstration of a point design. The sensor performance data will be delivered to the Formation Sensor Testbed (FST) and Formation Algorithm & Simulation Testbed (FAST). Design and analysis for the thermal shield technologies will be done at JPL, and materials development will be subcontracted to university or industry researchers.

A second goal for the Thermal Shield Testbed is to resolve optical stray light issues relative to the sun glint on the edge of the shield. Information gathered in the Thermal Shield Testbed will be delivered to the TPF Design Team for further evaluation.

Scope

- Measure RF properties of candidate thermal shield materials
- Identify a point design for the FF thermal shield
- Assess material viability for FF thermal shield

State of the Art TRL 2

Many materials exist that meet thermal requirements for the thermal shield. Many materials exist that meet the RF performance requirements for the formation sensors. No thermal shield has been demonstrated that meets both requirements simultaneously.

	Milestones	Performance Targets	TRL
2003	Receive initial design from the Design Team.		2
2004	Receive technology development requirements		2
2005	Materials selection and testing	Identify materials and measure their thermal and RF properties	3-4
2006	Identify thermal shield point design	Determine whether the material meets the RF, optical and thermal requirements.	4

Observatory Technology Plans

Cryocooler Technology

The TPF infrared interferometer concepts will require detectors cooled to ~6 K, with the optical bench cooled to ~18 K. In principle, this can be done with active coolers or stored cryogens, but the mission lifetime requirement of 5 years (and 10 year goal) leads the TPF project to seek the development of active coolers. The requirements for active cryocoolers for TPF are very similar to those of the James Webb Space Telescope (JWST). Additionally, TPF and JWST are very sensitive to vibrations of active components (such as compressors), and the instruments must be isolated from any vibration produced by mechanical cryocooler components. At this time no 10-year-life, 6 K /18 K coolers exist that would be suitable for use on TPF. However, extensive heritage from other programs exists and will be extended to meet TPF's needs.

Technology Challenges and Heritage

Over the last two decades, NASA, often in collaboration with the US Air Force, has funded cryocooler technology development in support of a number of missions. The largest use of coolers is currently in Earth Science instruments operating at medium to high cryogenic temperatures (50 to 80 K), reflecting the current state-of-the-art cryocooler technology. Since January 2002 we have seen two new long-life cryocooler systems launched into space to support NASA missions: the Northrop Grumman (formerly TRW) pulse tube coolers on the Atmospheric Infrared Sounder (AIRS) instrument, and the Creare NCS turbo Brayton cooler (on the Hubble Space Telescope's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument.

These recently launched coolers build upon the coolers of earlier NASA missions. These include coolers on the Improved Stratospheric and Mesospheric Sounder (ISAMS) instrument in 1991, the Measurements Of Pollution In The Troposphere (MOPITT) instrument and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument in 1999, and the Hyperion instrument in 2000. Additional coolers, such as the Northrop Grumman pulse tube coolers on the Tropospheric Emission Spectrometer (TES) instrument and the Ball Aerospace Stirling cooler on the High Resolution Dynamics Limb Sounder (HIRDLS) instrument, are in the queue for launch aboard NASA missions in the next couple of years. Also under development is a 1-watt at 18–20 K hydrogen sorption cryocooler for the Planck mission of the European Space Agency.

Advanced Cryocooler Technology Development Program

Technology Need Addressed

Cryocooler technology

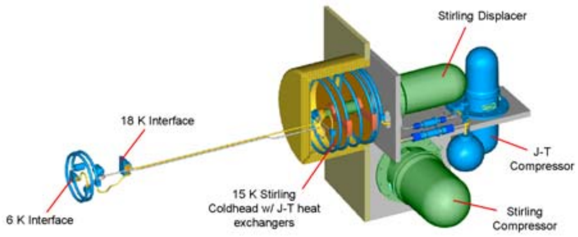
Objectives

Low vibration, long life, engineering model coolers will be developed and demonstrated with performance consistent with the needs of the TPF mission and other NASA astrophysics missions including possibly the James Webb Space Telescope and Constellation X. Coolers will provide ≈6 mW of cooling at 6K and ≈250mW of cooling at 18K.

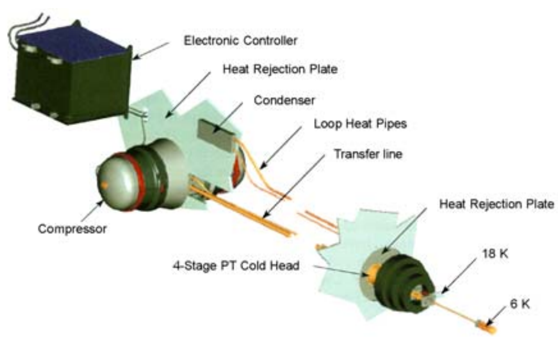
Approach

To develop the needed cryocooler technology, NASA initiated the Advanced Cryocooler Technology Development Program (ACTDP) under the leadership of the TPF project at JPL, and in collaboration with the NASA Goddard Space Flight Center. The ACTDP effort has been structured as a two-phase process containing a design phase followed by a demonstration phase of development and testing. The effort started with the generation of detailed requirements and specifications in summer 2001, leading to a community-wide request for proposals in November 2001, and the award of four parallel Phase-I contracts in April 2002. The Phase-I concepts presented by the four contractors are as follows:

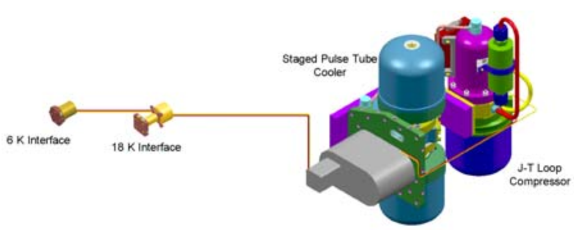
- Ball Aerospace: a 6 K/18 K Oxford-based J-T cooler precooled via a 15 K long-life Stirling cooler; this technology builds on the mature development history of Oxford-style linear compressors and Ball's flight development experience with the HIRDLS cooler



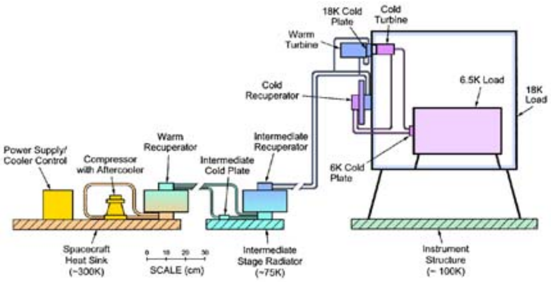
- Lockheed Martin ATC: a 6 K/18 K multi-stage Oxford-based pulse tube cooler; this technology builds on the mature development history of Oxford-style linear compressors and Lockheed's extensive development experience with Oxford-style Stirling and pulse tube cryocoolers.



- Northrop Grumman: a 6 K/18 K Oxford-based J-T cooler precooled via a 15 K long-life pulse tube cooler; this technology builds on Northrop Grumman's extensive development history of flight Oxford-style linear-compressor pulse tube coolers including AIRS, TES, and MTI.



- Creare, Inc.: a 6 K/18 K two-stage turbo-Brayton cooler that builds on Creare's successful NICMOS cooler recently installed on the Hubble Space Telescope and extensive research to extend the technology to lower temperatures.



In the design phase, each contractor developed a detailed system architecture for their 6K/18K cooler and a preliminary design with supporting laboratory test data sufficient to confidently enter into the hardware development and demonstration phase. The study phase culminated with a Preliminary Design Review (PDR) in September 2002, with the proposed cooler design documented in a final study report for evaluation by NASA and to serve as the primary basis for down-selection to the Demonstration Phase.

The concepts proposed by Ball Aerospace, Lockheed Martin, and Northrop Grumman were selected in December 2002 to advance into the Demonstration Phase. The initial focus will be on risk reduction and ultimately two coolers will be selected for full hardware development and demonstration. The hardware development and demonstration phase will involve detailed design, fabrication, performance and environmental testing, and delivery of an Engineering Model (EM) cryocooler system by the end of FY2005. The requested EM mechanical cryocoolers will be fully flight-like in form, fit, and function, and allow assessment of their ability to meet all key thermal, structural, and reliability/lifetime performance requirements.

In order to drive and operate the EM mechanical cooler, the demonstration phase of the ACTDP effort also includes the development and delivery of Brassboard cooler drive electronics that are flight-like in function (e.g., power and control functionality), but not in form. As a contract option, the contractors have also been asked to propose delivering an Engineering Model (EM) form of the cryocooler electronics. The EM electronics would fully demonstrate the form, fit, and function of flight model electronics to allow assessment of the ability of the circuit and mechanical design to meet key electrical, thermal, structural, and electromagnetic-interference performance requirements over the expected flight operating temperature range. Development of the EM electronics is not funded under the ACTDP, but flight projects have the option of funding their development.

Flight-model hardware fabrication and delivery is not within the scope of the ACTDP effort. However, ACTDP participants have been asked as part of the second phase activities, to estimate what additional resources and schedule would be needed to develop and deliver a fully flight qualified system (mechanical and electronic) meeting all interface, test, and documentation requirements for flight application.

Scope

- Through competitively awarded contracts, deliver:
  - Engineering model (EM) cooler system design
  - EM mechanical cryocooler
  - Brassboard cooler electronics
  - Ground Support Equipment for system testing
  - EM cooler system test
  - Flight cooler development plan

State of the Art TRL 2-3

At this time, no cooler has demonstrated capability to meet the TPF requirements. Analytical proof of concept and limited experimental proof of concept have been demonstrated. Higher temperature coolers based on similar technologies are now flying routinely in space.

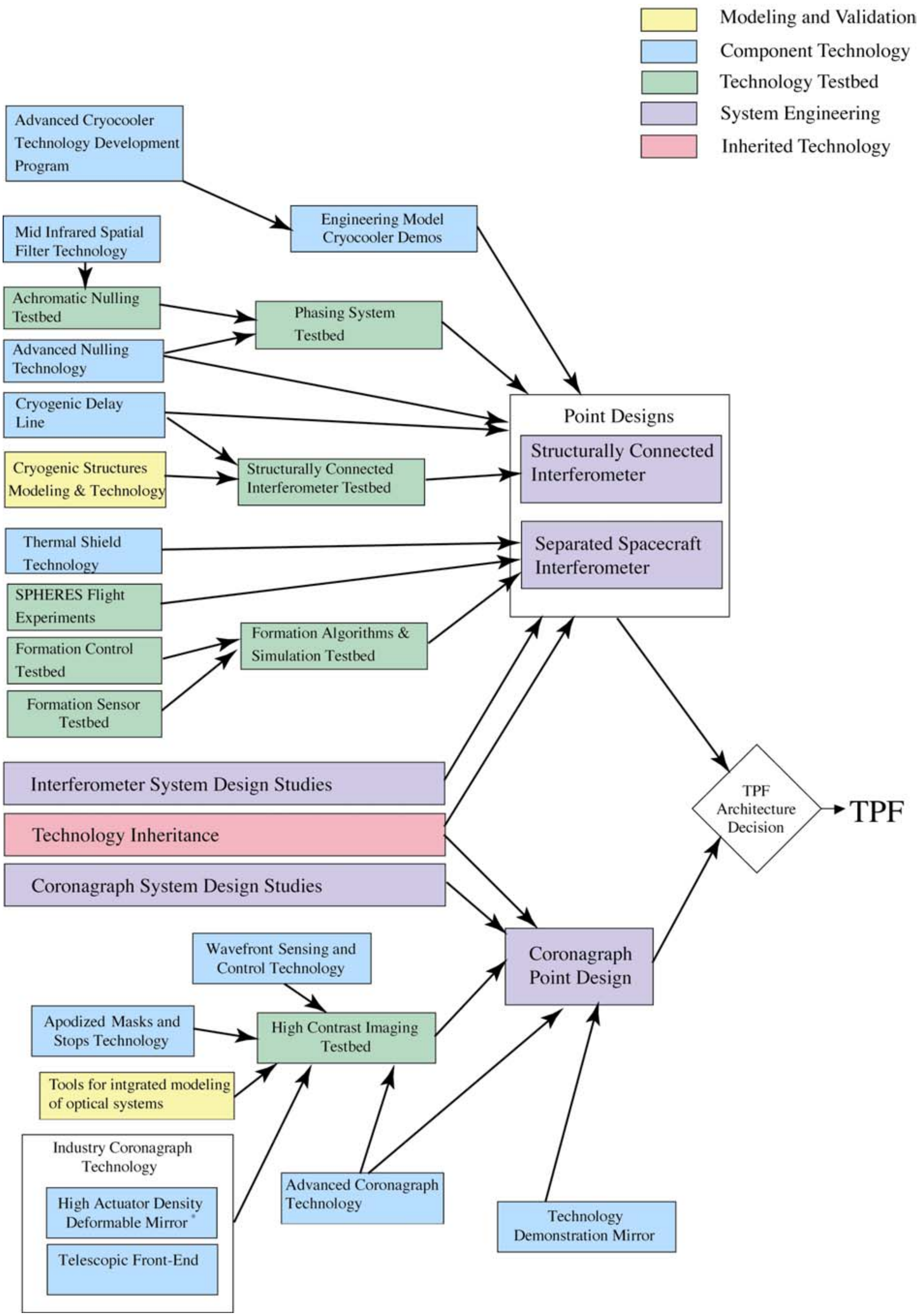
	Milestones	Performance Targets	TRL
2003	Select contractors for development phase ∆Preliminary Design Review	Risk reduction analysis	3
2004	Critical Design Review	Assembly and integration of engineering model coolers	4
2005	Engineering Model Cooler Delivery Test Coolers	Performance tests confirm that cryocoolers meet ACTDP specifications	5

TPF Technology Roadmap

The TPF architecture decision will be based, in part, on the results of the technology efforts described in this document, the technology inheritance available to TPF and the system engineering efforts of the design teams. All of these activities flow together to provide the information to support the architecture decision. This process can be represented pictorially in a flow diagram commonly referred to as a Technology Development Roadmap. A top level TPF Technology Development Roadmap has been developed that outlines the general approach and flow of the major elements of the plan leading to an architecture decision. The roadmap is shown on the following page.

This single page representation is supported by a great deal of detailed planning. All of the technology elements shown are described in this document along with annual milestones and performance targets (metrics) and performance goals (success criteria). Beyond that, each of the major elements has been divided into tasks with their own individually monitored plan, milestones, decision points, budget, schedule (in some cases down to level 4) and task lead. As of this writing, the TPF Project has 77 individual active tasks. This roadmap will be reviewed annually. Progress against plan will be established for the individual elements and tasks. An assessment will be made with input from the various project and external working groups and review boards as to whether termination, acceleration or redirection of efforts is warranted. The system and subsystem level error budgets developed by the design teams will play an important role in these assessments.

If significant change in the overall strategy described in this document is recommended, The Project will bring those recommendations forward to JPL and NASA management for approval/concurrence prior to implementation.


Modeling and Validation
Component Technology
Technology Testbed
System Engineering
Inherited Technology
Advanced Cryocooler Technology Development Program
Engineering Model Cryocooler Demos
Mid Infrared Spatial Filter Technology
Achromatic Nulling Testbed
Phasing System Testbed
Advanced Nulling Technology
Cryogenic Delay Line
Cryogenic Structures Modeling & Technology
Structurally Connected Interferometer Testbed
Point Designs
Structurally Connected Interferometer
Separated Spacecraft Interferometer
Thermal Shield Technology
SPHERES Flight Experiments
Formation Control Testbed
Formation Algorithms & Simulation Testbed
Formation Sensor Testbed
Interferometer System Design Studies
Technology Inheritance
Coronagraph System Design Studies
TPF Architecture Decision
TPF
Wavefront Sensing and Control Technology
Apodized Masks and Stops Technology
High Contrast Imaging Testbed
Coronagraph Point Design
Tools for intgrated modeling of optical systems
Industry Coronagraph Technology
High Actuator Density Deformable Mirror *
Telescopic Front-End
Advanced Coronagraph Technology
Technology Demonstration Mirror

Technology Heritage

The technologies described in this technology plan comprise only a part of the technology development required to launch a successful TPF mission. In addition to direct technology development, the TPF project is taking advantage of many other sources of advanced technologies that will meet TPF needs and be fully developed to near-flight requirements without additional support from TPF. Among these sources are other NASA space missions presently in development, such as the JWST and SIM. These technologies are identified in the table on the following page as sources of “direct” inheritance for TPF. The TPF Project expects that the directly inherited technologies will functionally meet the TPF mission needs, but require some engineering to meet the TPF specific form and fit.

Many of the technologies in development as part of the TPF pre-Formulation Phase technology development effort are evolutionary improvements over technologies that have been or will be developed for other space missions and ground-based systems. These technologies have been identified and are marked as “evolutionary” in the table on the next page. TPF will have to advance these technologies to meet mission needs, but is able to take advantage of substantial prior work and evolve them to meet the specific TPF needs.

Further sources provide lessons-learned and general knowledge, but do not provide a direct or evolutionary path to meet TPF’s requirements. Some of these, such are the integration of large optics and large cryogenic optics, are partially system engineering issues and partially technology development issues. The TPF project has identified these as “general” sources of technology inheritance on the following page.

As TPF’s requirements are more clearly defined and the requirements on specific technologies are adjusted through trade studies, the TPF Project will continue to track the inherited technologies to ensure that the mission requirements are met. Where the requirements and expected inheritance deviate, whether due to changes in TPF needs or changes in the development plans of the technology source, the TPF technology plan will be adjusted to compensate.

Source/Technology	D	E	G
SIM (NASA) http://sim.jpl.nasa.gov			
IR Interferometers			
Pathlength control		x	
Linear metrology	x		
Beam transport		x	
Pointing		x	
Precision structures			x
Vibration suppression		x	
Integrated modeling	x		
Interferometer I&T		x	
Space interferometry			x
Visible Coronagraphs			
Integrated modeling	x		
Vibration suppression		x	
JWST (NASA) http://www.ngst.nasa.gov/			
IR Interferometers			
Mid-IR detectors	x		
Large cryogenic mirrors/optics	x		
Cryogenic opto-mechanical devices	x		
Wavefront sensing and control	x		
Pointing (cryogenic)	x		
Precision deployable structures	x		
Vibration suppression	x		
Sunshade		x	
Passive cooling	x		
Integrated modeling	x		
Large cryogenics optics I&T		x	
Visible Coronagraphs			
Lightweight visible mirrors		x	
Wavefront sensing and control		x	
Pointing		x	
Precision deployable structures	x		
Vibration suppression		x	
Sunshade	x		
Integrated modeling	x		
Large optical system I&T		x	
HST (NASA) http://www.stsci.edu/hst/			
Visible Coronagraphs			
Visible/Near-IR detectors	x		
Large visible optics		x	
Pointing		x	
Large optics I&T			x
Coronagraph (on ACS/NICMOS)			x

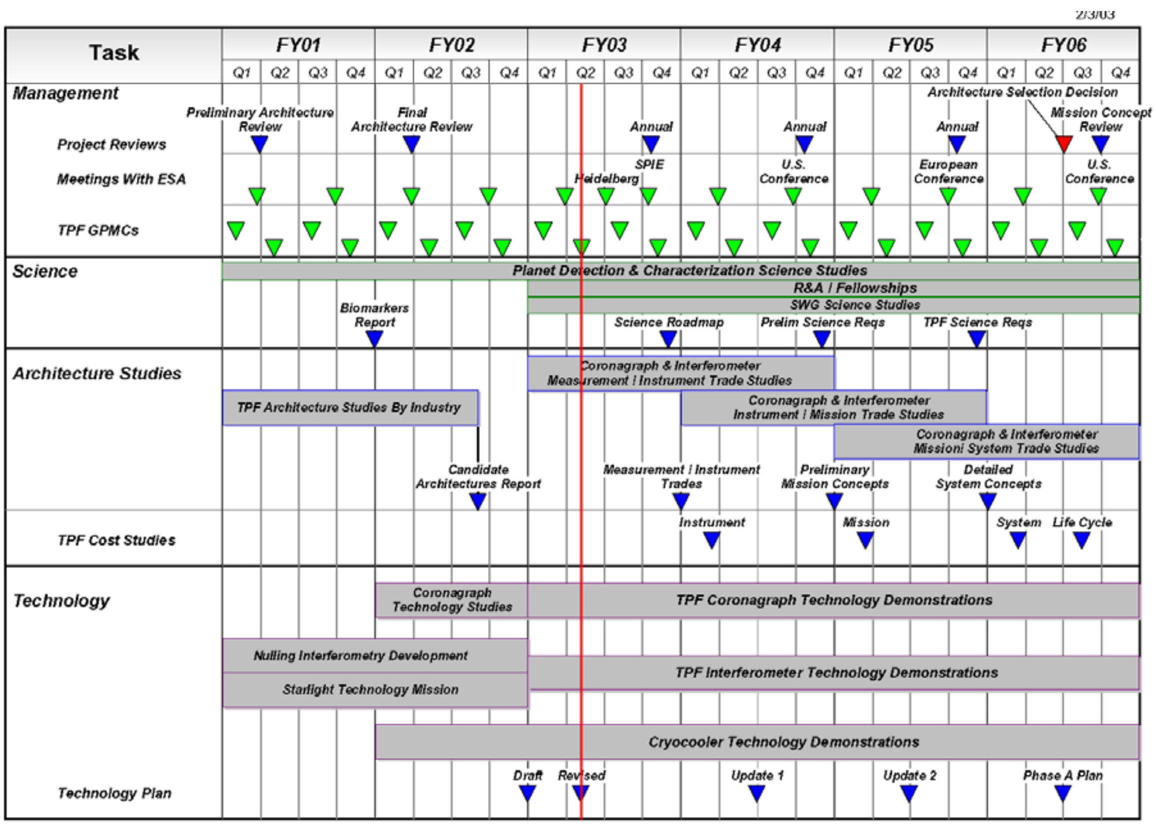
Categories of Inheritance:
Direct (D): applicable technology will be developed and function has been demonstrated adequately to assign a TRL 5 rating. It will be transferred to TPF with some engineering required to achieve form and fit.
Evolutionary (E): Relevant technology will be developed and demonstrated, but not adequately to assign a TRL 5 rating. It will be transferred to TPF and further evolved and extended to achieve TRL 5.
General (G): general knowledge and lessons learned that can be applied to more TPF-specific technology development.

Source/Technology	D	E	G
SIRTF (NASA) http://sirtf.caltech.edu/			
IR Interferometers			
Mid-IR detectors	x		
Large cryogenic mirrors/optics		x	
Cryogenic opto-mechanical devices		x	
Passive cooling		x	
Cryogenic optical system I&T		x	
Keck-I (NASA) and LBTI (NASA) http://keck.jpl.nasa.gov http://medusa.as.arizona.edu/lbtwww/lbt.html			
IR Interferometers			
Nulling		x	
Pathlength Control		x	
Beam Transport		x	
Pointing		x	
Interferometry			x
Interferometer I&T			x
Visible Coronagraphs			
Large Telescopes			x
StarLight (NASA) http://Planetquest.jpl.nasa.gov/StarLight/starlight_index.html			
Formation Flying Technology			
Integrated architecture		x	
Formation sensors (range/bearing)		x	
Attitude & Translation (6DOF) guidance		x	
Precision formation control for interferometry		x	
Formation acquisition/collision avoidance		x	
Precision actuation during sustained observation		x	
Modeling & Simulation	x		
Separated Spacecraft Interferometry			
Inter-s/c metrology	x		
Pathlength control		x	
Stable fringe lock		x	
Formation Flying Demonstrations			
Techsat 21 (AFRL)			
Range control/knowledge		x	
Angular control/knowledge		x	
Control algorithms		x	
Constellation flight			x
SPHERES (MIT/DARPA)			
Control algorithms		x	
ST6/XSS11 [ARX] (AFRL/NASA)			
Relative position sensors		x	
Control algorithms		x	
Demonstration of Autonomous Rendevous Technologies (NASA)			
Advanced guidance sensor		x	
Orbital Express (NASA/DARPA)			
Relative position sensors		x	

TPF Project Schedule

Project Pre-Phase A Schedule

The TPF Project Schedule for the pre-phase A period out to FY2006 is shown below. The TPF Technology Plan is paced to deliver the data and information needed to select an architecture in 2006, enter Phase A in 2007 and ultimately launch in ≈ 2015, as depicted in the master schedule below.



TPF Project Budget

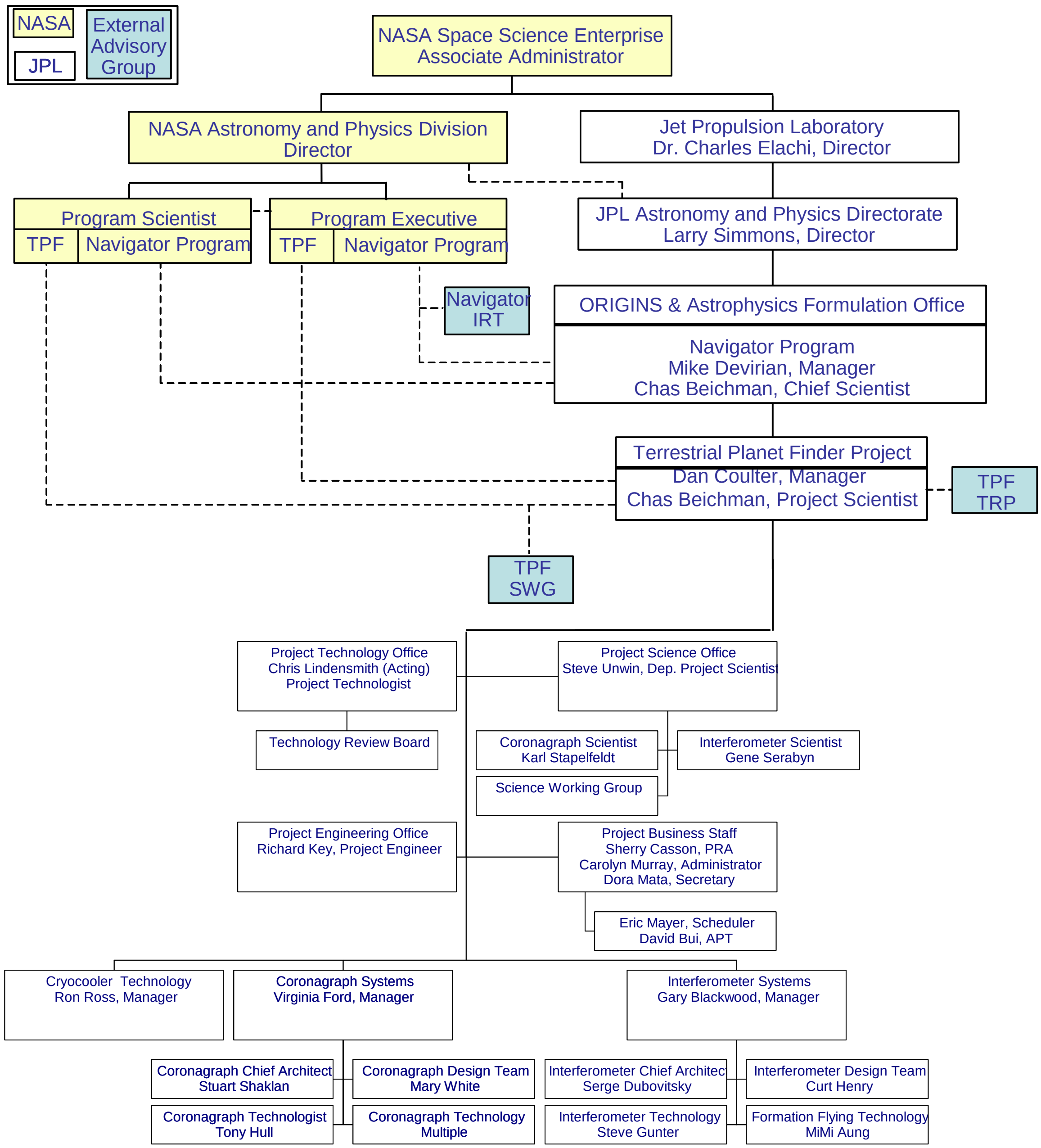
Project Pre-Phase A Budget

The TPF Project Budget for the pre-phase A period out to FY2006 is shown below. This budget is consistent with the current (as of this writing) pre-03-POP plan submitted to NASA.

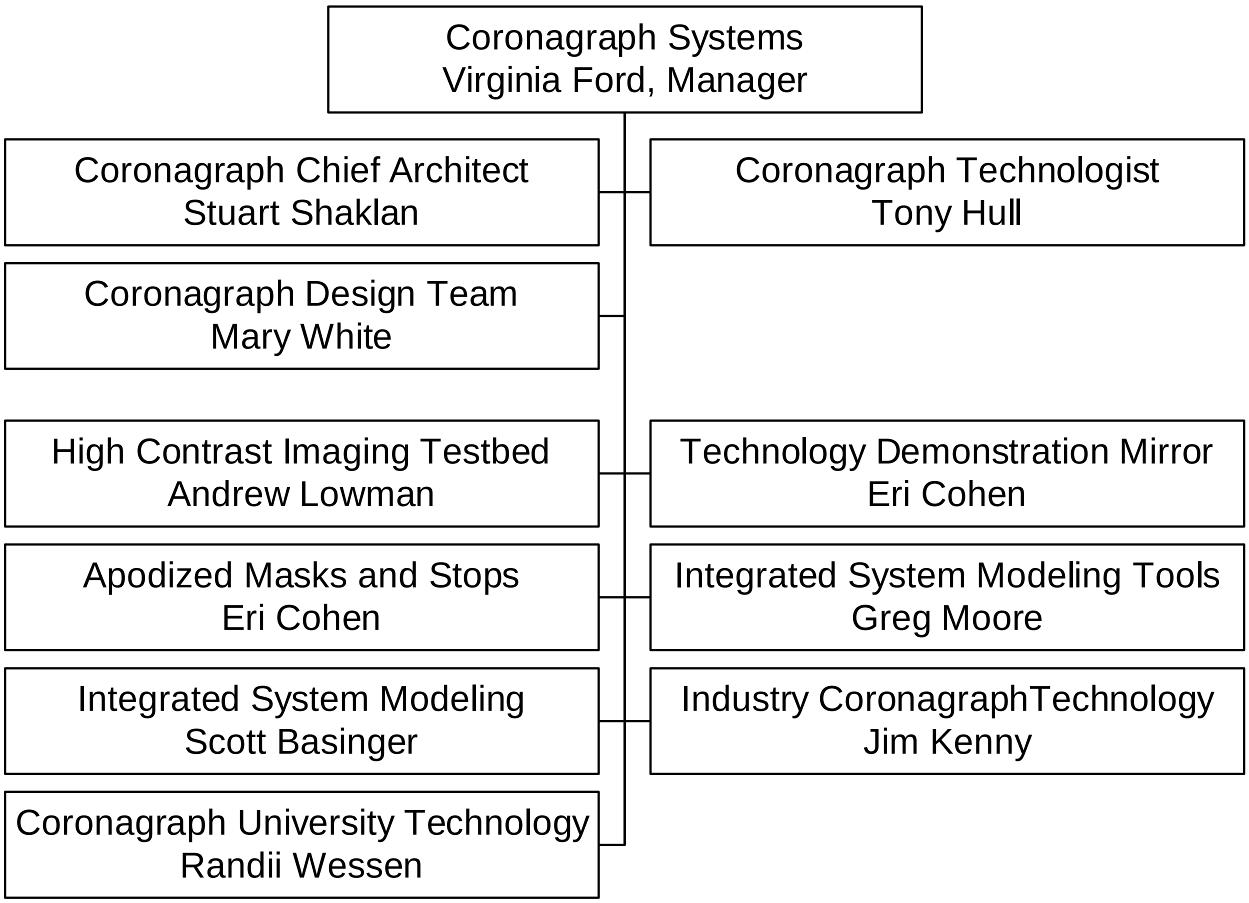
Project Management:	$9.1M
Project Reserve:	$9.1M
Project Engineering:	$2.3M
Project Science:	$8.1M
(not including additional science grants ≈$7.9M)	
Coronagraph Systems:	
System Studies	$11.0M
Technology	$42.0M
Interferometer Systems:	
System Studies(SCI/ FFI)	$19.4M
Core Technology	$19.8M
Structurally Connected Interferometer Technology	$14.6M
Formation Flying Interferometer Technology	$25.4M
Cryocooler Technology:	$18.0M
TOTAL	$178.8M

Appendices

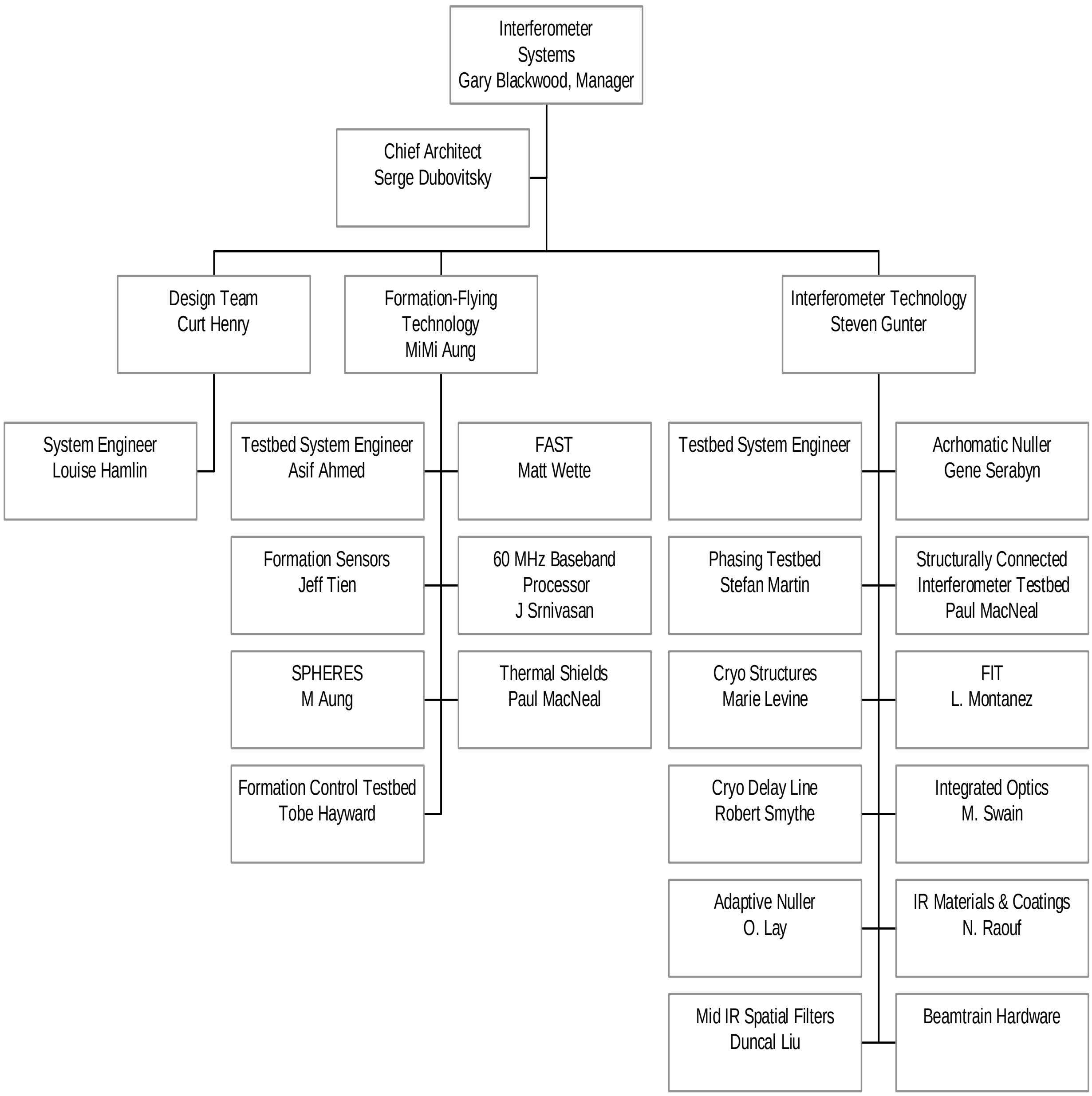
A1- TPF Project Organization



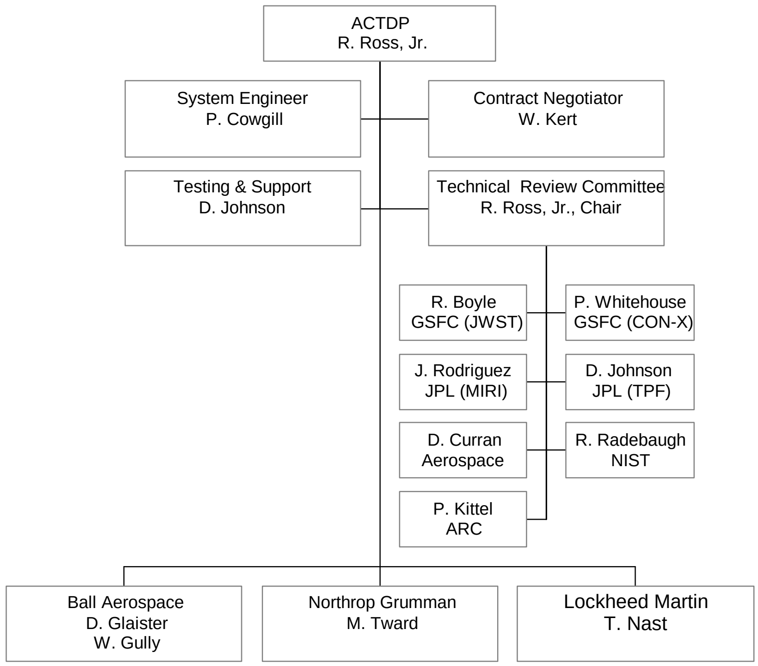
Coronagraph Systems Organization



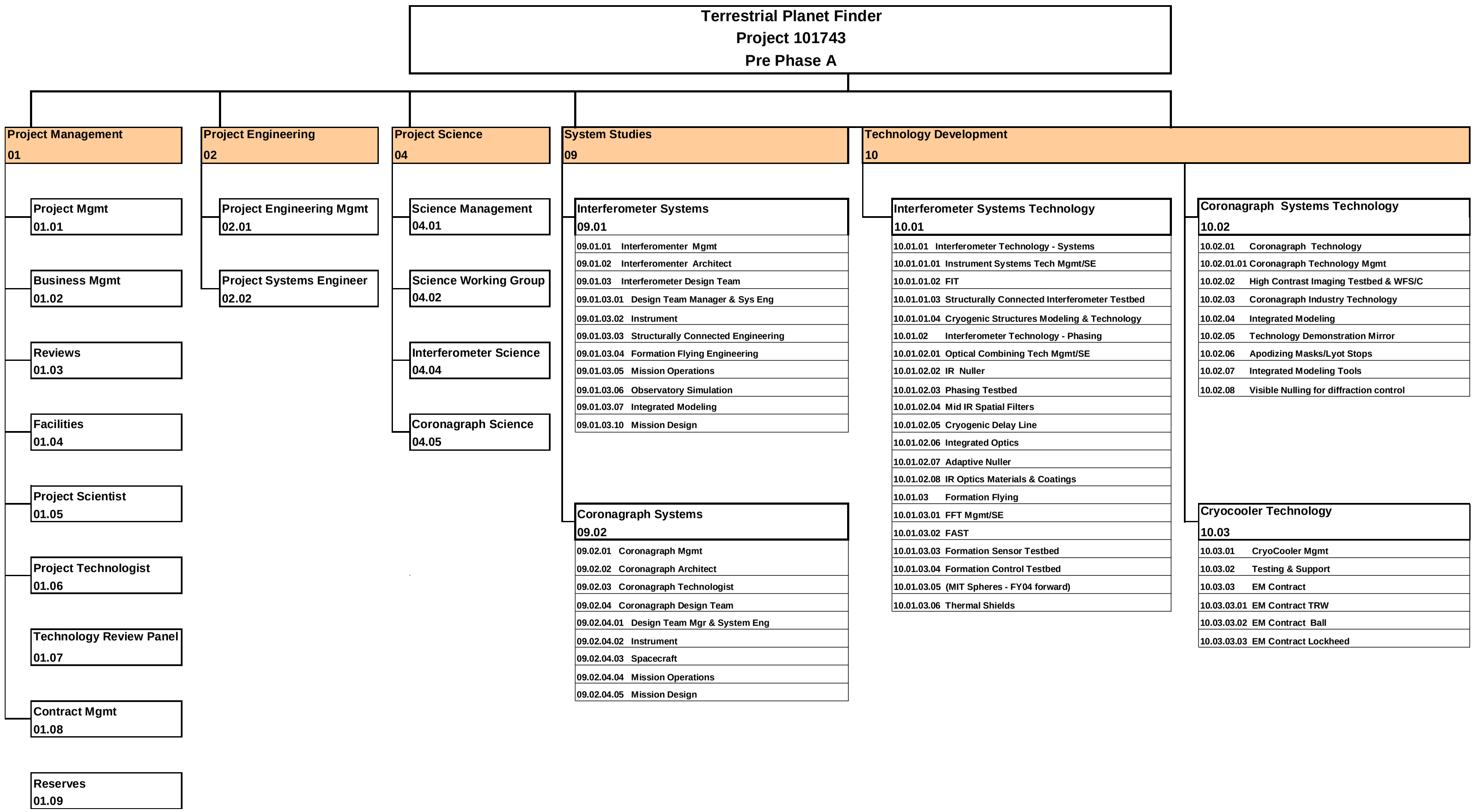
Interferometer Systems Organization



Advanced Cryocooler Technology Development Organization



A2- Project Work Breakdown Structure



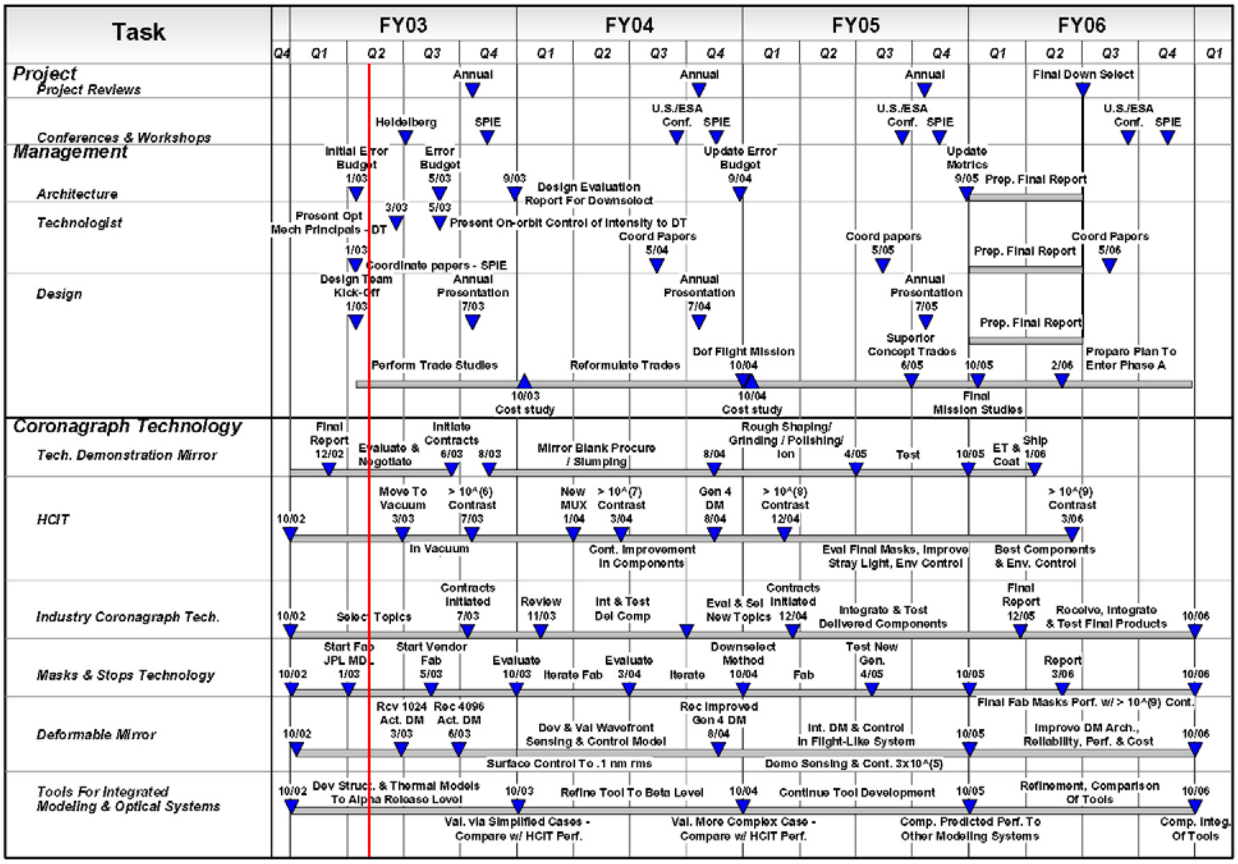
A3- TPF Technology Budget

The current working TPF Technology development budget, based on the pre-03 POP exercise, is shown below. Detailed implementation plans have been developed for each task and reviewed by the project on an annual basis. Annual budget allocations will be made based on the available funds, procurement costs, project priorities and implementation plans.

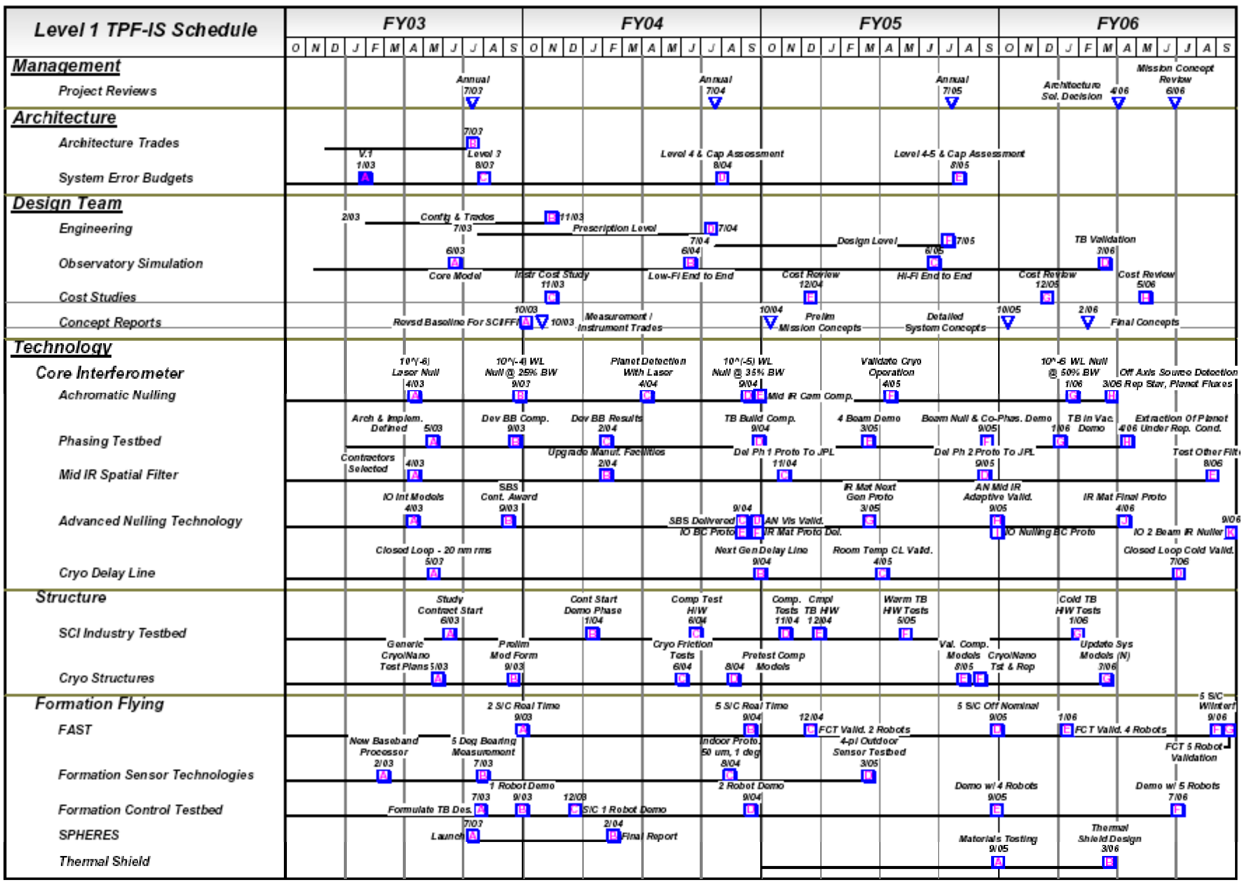
Coronagraph Technology	**8.7**	**11.0**	**11.4**	**9.6**	**42.0**
Technology Demonstration Mirror	2.38	4.63	5.89	3.99	16.9
High Contrast Imaging Testbed	2.62	2.63	2.32	1.88	9.4
Wavefront Sensing & Control Technology	0.70	0.95	0.33	0.91	2.9
Industry Coronagraph Technology	1.13	1.13	1.40	1.30	5.0
Apodized Masks and Stops Technology	1.32	1.10	0.94	1.00	4.4
Tools for Integrated Modeling of Optical Systems	0.52	0.53	0.54	0.56	2.2
Advanced Coronagraph Technology	0.33	0.35	0.35	0.28	1.3
Interferometer Technology	**11.2**	**17.2**	**16.6**	**14.7**	**59.7**
Interferometer Core Technology	**4.20**	**7.10**	**4.82**	**3.64**	**19.76**
Management and Testbed System Engineering	0.32	0.49	0.52	0.54	1.9
Achromatic Nulling Testbed	1.76	2.16	1.02	0.47	5.4
Advanced Nulling Technologies	0.53	0.56	0.57	0.35	2.0
Mid IR Spatial Filter Technology	0.39	0.57	0.51	0.47	1.9
Cryogenic Delay Line Testbed	0.25	0.25	0.30	0.30	1.1
Phasing System Testbed	0.96	3.07	1.90	1.51	7.4
Structurally-Connected Interferometer Technology	**1.33**	**2.78**	**4.22**	**6.25**	**14.6**
Industry Interferometer Testbeds	0.84	1.98	3.21	4.97	11.0
Cryogenic Structures Modeling	0.49	0.80	1.01	1.29	3.6
Formation Flying Interferometer Technology	**5.7**	**7.3**	**7.6**	**4.8**	**25.4**
Management and Testbed System Engineering	0.66	0.58	0.74	1.23	3.2
Formation Algorithms & Simulation Testbed	1.72	1.21	2.72	2.36	8.0
Formation Sensor Technology	1.49	2.23	0.88	0.32	4.9
Formation Control Testbed	1.72	3.16	2.89	0.67	8.4
SPHERES Flight Experiments	0.10	0.14	0.12	0.12	0.5
Thermal Shield Testbed	0.00	0.00	0.25	0.10	0.4
Cryocooler Technology	**6.0**	**6.6**	**4.1**	**1.3**	**18.0**
Total ($M)	**19.9**	**34.8**	**32.1**	**25.6**	**119.7**

A4- TPF Schedules

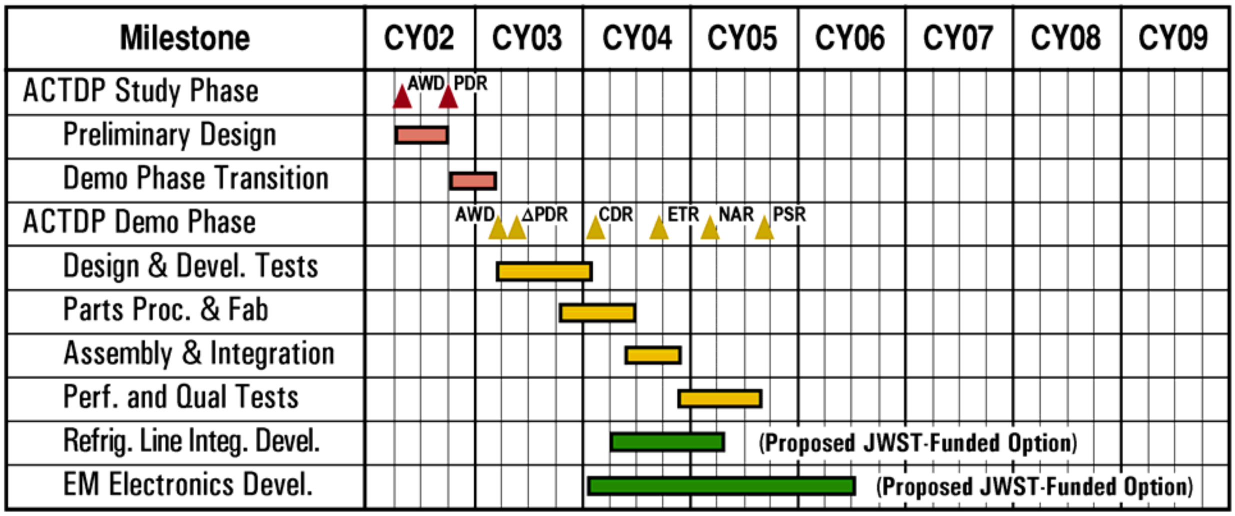
Coronagraph Systems Level 1 Schedule



Interferometer Systems Level 1 Schedule



Advanced Cryocooler Technology Development Program Level 1 Schedule



A5- TPF Science Working Group

TPF Science Working Group	
Name	**Institution**
Charles Beichman (Chair)	Jet Propulsion Laboratory
Dana Backman	Franklin and Marshall College
Robert Brown	Space Telescope Science Institute
Christopher Burrows	Consultant
William Danchi	NASA Goddard Space Flight Center
Malcolm Fridlund	ESA/ESTEC
Eric Gaidos	University of Hawaii at Manoa
Philip Hinz	University of Arizona
Kenneth Johnston	US Naval Observatory
Marc Kuchner	Smithsonian Astrophysical Observatory
Doug Lin	University of California, Santa Cruz
Jonathan Lunine	University of Arizona
Victoria Meadows	Jet Propulsion Laboratory
Gary Melnick	Smithsonian Astrophysical Observatory
Bertrand Mennesson	Jet Propulsion Laboratory
David Miller	Massachusetts Institute of Technology
Charley Noecker	Ball Aerospace and Technologies Corp.
Sara Seager	Carnegie Institution of Washington
Eugene Serabyn	Jet Propulsion Laboratory
William Sparks	Space Telescope Science Institute
David Spergel	Princeton University
Wesley Traub	Smithsonian Astrophysical Observatory
John Trauger	Jet Propulsion Laboratory
Ted von Hippel	University of Texas, Austin
Neville Woolf	University of Arizona

A6- TPF Technology Review Panel

TPF Independent Technology Review Panel		
Name	**Institution**	**Area of Expertise**
Michael Krim (Chair)	Perkin-Elmer, retired	Large optical systems
Pierre Bely	Space Telescope Science Institute, retired	Large optical systems
Jim Breckinridge	Jet Propulsion Lab	ORIGINS Theme Technologist
Chris Burrows	Consultant	Coronagraph systems
Mark Colavita	Jet Propulsion Laboratory	Interferometry systems
Dick Dyer	Schafer Corporation	Large optical systems, precisions wavefront control
Dave Hyland	University of Michigan	Precision formation flying
Ken Johnston	US Naval Observatory	Interferometry systems
John Lipa	Stanford University	Cryogenic systems
Michael Lou	Jet Propulsion Laboratory	Mechanical systems & structures

A7- NASA Technology Readiness Level Definitions

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL concept is based on a general model for technology maturation that includes: (a) research in new technologies and concepts (targeting identified goals, but not necessary specific systems), (b) technology development addressing specific technologies for one or more potential identified applications, (c) technology development and demonstration for each specific application before the beginning of full system development of that application, (d) system development (through first unit fabrication), and (e) system 'launch' and operations.

TRL 1: Basic principles observed and reported

Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2: Technology concept and/or application formulated

Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept

Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4: Component/subsystem validation in laboratory environment

Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5: System/subsystem/component validation in relevant environment

Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6: System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)

Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

TRL 7: System prototyping demonstration in an operational environment (ground or space)

System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

TRL 8: Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space)

End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9: Actual system "mission proven" through successful mission operations (ground or space)

Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

A8- Acronyms

ACTDP	Advanced Cryocooler Technology Development Program
AFF	Autonomous Formation Flying
AIRS	Atmospheric Infrared Sounder
ARR	Assembly Readiness Review
ASO	Astronomical Search for Origins
ASTER	Advanced Spaceborne Thermal Emission Reflection Radiometer
ATC	Advanced Technology Center
ATLO	Assembly, Test, and Launch Operations
AWD	Award
CDR	Critical Design Review
DARPA	Defense Advanced Research Projects Administration
DM	Deformable Mirror
DOD	Department of Defense
EM	Engineering Model
ESA	European Space Agency
ExNPS	Exploration of Neighboring Planetary Systems
FACS	Formation Algorithms & Control System software
FAST	Formation Algorithms & Simulation Testbed
FCT	Formation Control Testbed
FDDS	Formation Dynamics & Devices Simulation software
FF	Formation Flying
FIT	Formation Interferometer Testbed
FST	Formation Sensor Testbed
FWHM	Full Width at Half Maximum
FY	Fiscal Year
HCIT	High Contrast Imaging Testbed
HIRDLS	High Resolution Dynamics Limb Sounder
HST	Hubble Space Telescope
ICT	Industry Coronagraph Technology Testbed
IMOS	Integrated Modeling of Optical Systems
IO	Integrated Optics
IR	Infrared
ISAMS	Improved Stratospheric and Mesospheric Sounder
JPL	Jet Propulsion Laboratory
J-T	Joule-Thomson
JWST	James Webb Space Telescope
LBT	Large Binocular Telescope
LBTI	Large Binocular Telescope Interferometer
LRR	Launch Readiness Review
MATLAB	Matrix Laboratory
MIR	Mid-Infrared
MIT	Massachusetts Institute of Technology
MMZ	Modified Mach-Zehnder
MOPPITT	Measurements Of Pollution In The Troposphere
NAR	Non-Advocate Review
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis Program
NCS	NICMOS Cooling system
NGST	Next Generation Space Telescope (see also JWST)
NICMOS	Near Infrared Camera and Multi-Object Spectrometer

NRA	NASA Research Announcement
OPD	Optical Path Difference
OSS	Office of Space Science
PDR	Preliminary Design Review
PMSR	Preliminary Mission Systems Review
POP	Program Operating Plan
PSR	Pre-Ship Review
P-V	Peak to Valley
QE	Quantum Efficiency
R&A	Research & Analysis
RMS	Root Mean-Square
SBIR	Small Business Innovative Research
SIRTF	Space Infrared Telescope Facility
SIM	Space Interferometry Mission
SPHERES	Synchronized Position Hold Engage and Reorient Experimental Satellites
SPIE	International Society for Optical Engineering
SWG	Science Working Group
TDM	Technology Demonstration Mirror
TES	Tropospheric Emission Spectrometer
TPF	Terrestrial Planet Finder
TRL	Technology Readiness Level
TRP	Technology Review Panel
WFE	Wavefront Error
WFS	Wavefront Sensor
WFS&C	Wavefront Sensing and Control

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